An alternative approach to evaluating inter-basin water transfer links: A case study of the Inter-Linking of Rivers Project in India

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A thesis submitted to fulfil the requirements for the degree of

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Water managers face significant challenges in managing water supply and are constantly looking for new ways to meet demand. Inter-basin water transfer (IBWT) is a preferred solution, especially in developing countries such as India. Proponents have praised IBWT for its benefits but critics have raised several concerns, among which, concerns related to the IBWT decision-making process are fundamental. The proposed Inter-linking of Rivers project (ILR) in India has been extensively criticised for its decision-making process. This thesis evaluated the decision-making process of two ILR Projects in India, namely the Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR links, using data and tools available in the public domain.

The research acquired a holistic and multi-disciplinary understanding of the catchments involved in the two ILR projects. The knowledge gained assisted in identifying key inputs, informing assumptions and explaining the research outcomes. Based on the best-practices in the IBWT field, the study developed an integrated appraisal of potential annual and seasonal surplus/deficit of water in the donor and recipient catchments of both links. Both ILR links and their catchments were simulated for their annual and seasonal performance assessments under a range of current and future water management scenarios. The simulation outputs were used to assess the risks in meeting water requirements by the catchments and the links. The ILR links were also assessed for their vulnerabilities in meeting the proposed water transfer amount. The research critiqued existing ILR plans and found that the ILR planners have over-estimated the water surplus in the donor catchments of both links and that the links will fail to meet their projected aspirations. The donor catchments themselves need efforts to ensure their current and foreseeable future water demand. The recipient catchments show no urgent need to import water from another basin currently or in the foreseeable future; although low water availability has been noted in them during the non-monsoon season which needs attention. Thus, the ILR planners are advised to reconsider their decisions and revisit their planning.

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Table of Contents

List of figures

List of tables

Abbreviation

AMQ	Annual mean flow
CGWB	Central Ground Water Board
CWC	Central Water Commission
CSE	Centre for Science and Environment
GSI	Geological Survey of India
GWP	Global Water Partnership
GOI	Government of India
GOJ	Government of Jharkhand
HOC	Hydrological Observation Centres
IMD	Indian Meteorological department
IBWT	Inter-basin water transfer
ILR	Inter-linking of Rivers
MSL	Mean Sea Level
MSME	Ministry of Micro Small & Medium Enterprises
MoWR	Ministry of Water Resources
MMQ	Monthly mean flow
NOAA	National Oceanic and Atmospheric administration
NRSC	National Remote Sensing Centre
NWDA	National Water Development Agency
OGD	Open Government Data (by Government of India)
PET	Potential Evapo-Transpiration
PFR	Pre-feasibility reports
RRSSC	Regional Remote Sensing Service Centre
RCP	Representative Concentration Pathways
S-SK	Sankh-South Koel
S-SK-Sr	Sankh-South Koel-Subarnarekha
SRTM	Shuttle Radar Topography Mission
SK-Sr	South Koel-Subarnarekha
SCI	Supreme Court of India
WA	Water Availability
WD	Water Demand
WEAP	Water Evaluation And Planning
India-WRIS	Water Resource Information System (by Government of India)
WRM	Water Resource Management

Important terms

Although the present thesis addresses one of the crucial water management problems, it also weaves some important themes in the present research which are defined below:

Hybridity – Latour (1993) introduced the concept of hybridity in which he mixed nature and human culture. Swyngedouw (1999) first used this Latourian concept in studies related to water management of Spain and assessed the associated natural and social processes in the region. Bourblanc & Blanchon (2014) stated that water management of any region is hybrid in nature as it covers natural as well as socio-economic aspects of the region.

Wicked Problems – Wicked problems involve various conflicting stakeholders with embedded opposing stances, complexity and considerable uncertainties and water management is a good example of such problems (Lund 2012). Wicked problems have no clear technical and policy solution (Lach et al. 2005). They require constructive discussion and consensus process among its stakeholders which are difficult targets to achieve (Lund 2012).

Dublin Principles – The Dublin Statement on water and sustainable development, commonly known as The Dublin Principles, are set of recommendations for sustainable management of water at local, national and international scale (details in WMO 2017). It recommends data democratisation, encourages transparency and promotes public participation in planning and management of water resoruces (Solanes & Gonzalez-Villarreal 2009).

Declaration and statement of copyright

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where is relevant, material from the work of others has been acknowledged.

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Dedicated to hope and positivity

Chapter 1 Introduction

1.1 The context of water transfer

Water is unevenly distributed at a range of spatial and temporal scales across the globe and so too is demand (Gupta & van der Zaag 2008). Continuous growth of the world economy and exponentially growing populations intensify the demands placed on water resources (Bourn 1999). However, locations of increasing water demand do not always coincide with spatial availability of ample water (Cox 1999) and in many areas the demand is outstripping the supply (Gupta & van der Zaag 2008). As a result, the world is facing an intense challenge to fulfil the growing demand for safe, reliable water supplies (WWF 2007). The challenge has been further aggravated by water scarcity in many countries (McNally & Tognetti 2002), resulting in decreasing fresh water availability across the globe (Döll et al. 2003; Parish et al. 2012). A sustainable water supply thus poses various challenges to policy makers and water managers (Feldman 2001); supply-oriented solutions have thus become the preferred option for managing water (Bhaduri et al. 2008) and are widely implemented in many regions around the world (Gupta & van der Zaag 2008).

Inter-basin water transfer (IBWT) is one of the most sought-after supply-oriented solutions employed to sustain water for use (Gupta & van der Zaag 2008). IBWT moves excess water from geographically separate water-surplus basins to water-deficit basins (Davies et al. 1992) using engineering structures (Micklin 1984; Snaddon & Davies 2006) to assure water supply in high water demand areas (Gupta & van der Zaag 2008). These projects have been utilised since ancient times (Gichuki & McCornick 2008) with the earliest known water transfer link built in 2500 BC to connect the River Tigris and River Euphrates (Meador 1992). The approach gained significant momentum from the 19th century onwards and received significant attention in the 20th century (Howe & Easter 1971; Ghassemi & White 2007) in both developed and developing countries[1] (Figure 1.1).

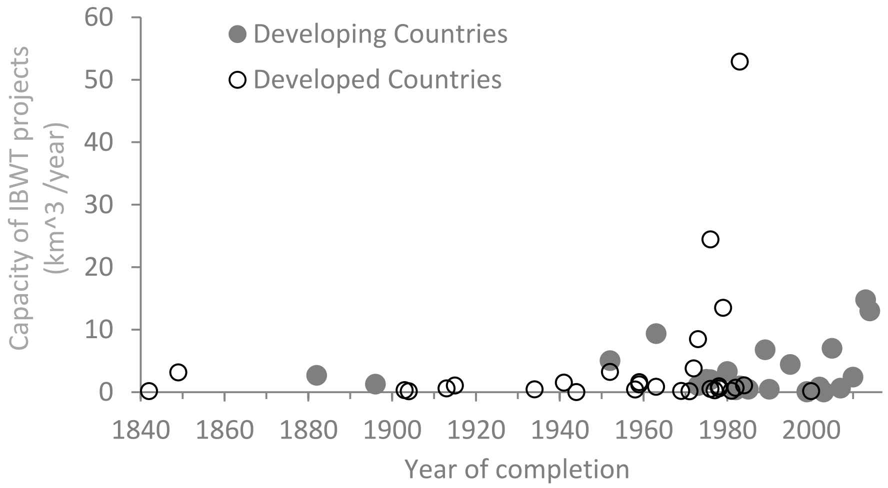


Figure 1.1: Interbasin water transfer (IBWT) projects[2] along with their capacity during 1840-2017 in developed and developing countries.

In 2005, approximately 14% of the total water withdrawal from rivers in the world was for IBWT and it is expected to grow to 25% by 2025 (ICID 2005, at Gohari et al. 2013, pg. 24). Selected major projects from across the world are outlined in Figure 1.2 (For details see Appendix A.1).

1.2 Inter-basin water transfer: management

IBWT has brought economic prosperity to many areas around the world (Thatte 2009). Such interventions are mostly multi-purpose projects covering water need for municipal, industrial, irrigation requirements and hydro-electricity generation (UNESCO 1999). Although proponents of IBWT claim it to be highly beneficial (Ghassemi & White 2007), critics have raised several concerns, have questioned the practicality of these supply-side projects (Gupta & van der Zaag 2008) and called them a product of interconnection between politics, science and financers (Gumbo & van der Zaag 2002).

[1] Based on Department of Economic and Social Affairs, United Nations Secretariat (UN/DESA) (2014).
[2] Compiled from studies by UNESCO (1999), Ghassemi & White (2007)and Zhang et al. (2015).

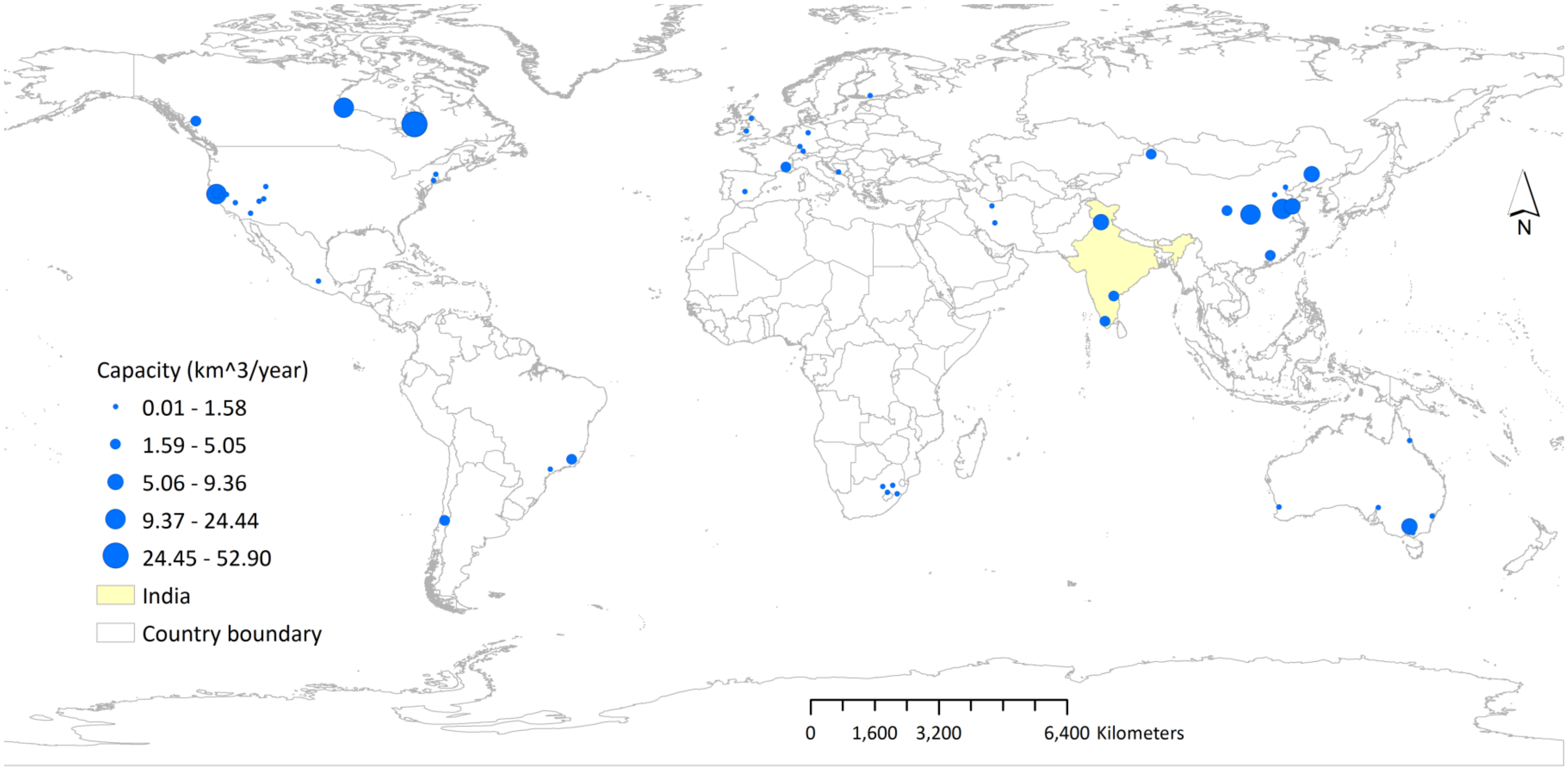


Figure 1.2: Major Inter-basin Water Transfer (IBWT) Projects in World.

Note: The countries included in this map are based on UNESCO (1999), Ghassemi & White (2007) and Zhang et al. (2015). India, being location for the case-study of this research, has been highlighted in yellow. The IBWT schemes should be represented by line symbols; however, given the scale of map, line symbols will not represent them clearly, thus point symbols have been used. The exact locations for most of the projects are not always publicly available; therefore, the map shows their most probable middle positions.

Some of the controversial issues raised by critics include: the decision-making and justification of water transfer (Smakhtin et al. 2007; Amarasinghe 2012) including transparency (Cosens 2010), little or no public participation (Pittock et al. 2009), environmental and ecological disturbances (Davies et al. 1992; Baggett 2009), inundation or drying up of land with environmental and other important values (Alagh et al. 2006), huge costs (Gupta & van der Zaag 2008), un-equal distribution of cost-benefits (Howe & Easter 1971; Chopra 2006), potential impact of projected climate change (Brekke et al. 2008; Maknoon et al. 2012), sedimentation/ siltation (Kibiiy & Ndambuki 2015), and resettlement and rehabilitation of effected communities (McCully 2001). Furthermore, concerns have been raised regarding the impact of IBWT schemes on socio-economic development of upstream (Al-Faraj & Scholz 2014) and downstream catchments of the transfer point (Das 2006; Richter et al. 2010), along with socio-cultural aspects of the areas impacted by altered supply (Zhang et al. 2009).

The critical concerns for IBWT projects are intertwined and show hybridity (Swyngedouw 1999) and wickedness (Lund 2012) and fall into the multi-disciplinary arena for their planning and management (Yevjevich 2001). These projects require an integrated approach for their planning and management (Golubev & Biswas 1977; Schumann 1999; Kibiiy & Ndambuki 2015). However, this need for integrated analysis and assessment of IBWT projects has been ignored by water managers in most cases (Gupta & van der Zaag 2008) and only a few researchers have focused on exploring IBWT from an integrated perspective (e.g. Bharati et al. 2008). Therefore, there is a pressing need for in-depth multi-disciplinary studies with an integrated approach for planning and management of these large water infrastructures (Golubev & Biswas 1977; World Commission on Dams (WCD) 2000; Gupta & van der Zaag 2008; Thatte 2009; Amarasinghe & Sharma 2008; Ribeiro Neto et al. 2014). The research undertaken for and presented in this thesis undertakes an integrated analysis of one of the most ambitious planned IBWT projects, the Inter Linking of Rivers (ILR) project in India.

1.3 The case of Inter-linking of Rivers (ILR) project in India

India is one of the most rapidly developing economies with a swiftly increasing population and is facing growing water demand from various users, despite good surface water potential at the national scale (Mall et al. 2006). This problem has been further escalated by factors such as a complex tropical monsoon climate system, which is notorious for its frequent drought and flooding events, uneven spatio-temporal distribution of water resources and topographical constrictions (Gaur & Amerasinghe 2011). The concurrent pattern of drought in one region yet flooding in another leads to significant hardship for those people affected (NWDA 2016). As a potential solution for these problems, water managers in India have opted for water transfer projects since the 19th Century (Thatte 2006). Following this approach, several IBWT projects which are collectively known as the 'Inter Linking of Rivers (ILR)' project, are being planned under the supervision of the National Water Development Agency (NWDA) to combat projected future water and food demand by 2050 (NWDA 2016).

The ILR project was first proposed by the British military engineer Sir Arthur Cotton in 1858 (NWDA 2016) and since then it has fascinated Indian water managers and decision makers (Pasi 2012). This audacious project was embraced by the national perspective plan in 1980 (Shah et al. 2008) but subsequently its progress slowed for various reasons, including a long planning process as well as the concerns raised by critics (Thatte 2006; Prabhu 2008). In 2002, under instruction from the Supreme Court of India (SCI), the Government of India (GOI) accelerated the work on the ILR projects (NWDA 2016) despite the disputed benefits and critical concerns (Jolly 2016). Since 2014, the work has been heavily pushed by the newly formed government (Jolly & Probe International 2016), making it one of the biggest challenges in current Indian water resource management (WRM).

The ILR project is 'unique [for] its unrivalled grandiosity' (Shah et al. 2008, p.6). In total, it aims to move 173 km^3 of water per annum through 15000 km of new waterways (Jolly 2016) which will make it the largest water resource project in the world (Bandyopadhyay & Perveen 2008) (Figure 1.3). The project has two major sectors: the Himalayan and the Peninsular components; and it is being carried out on two administrative levels: Inter-state (among several states) and Intra-state (within one state completely). There are 30 IBWT links at the inter-state level and 32 IBWT links at the intra-state level (NWDA 2015).

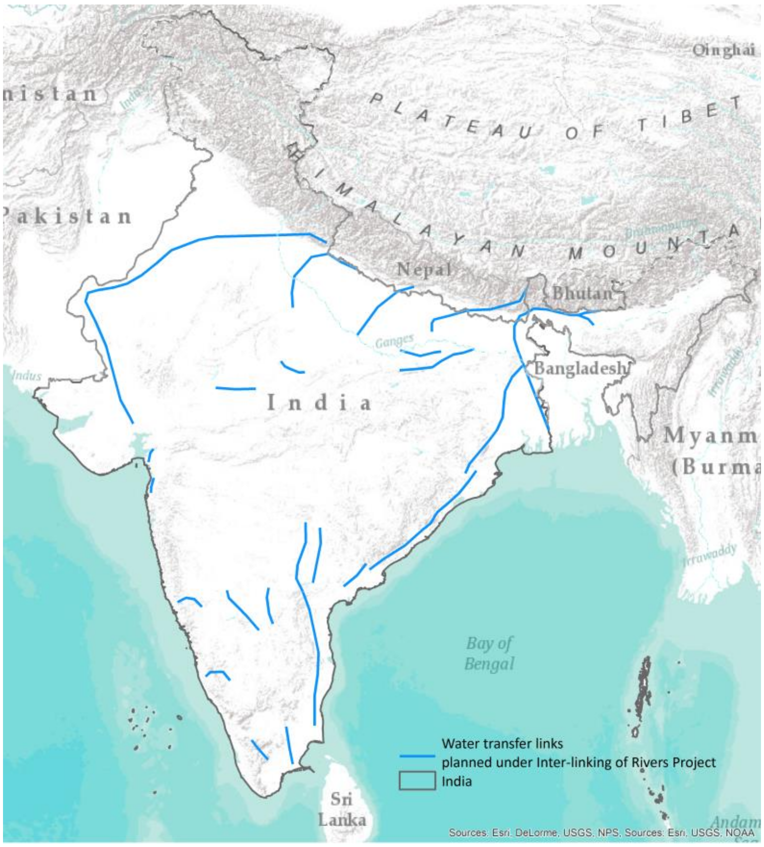


Figure 1.3: Inter-linking of Rivers (ILR) Project showing water transfers links (individual/combined) at inter-state level[3] (modified after NWDA 2016).

Note: The map is prepared by using ArcGIS base map data (See Esri 2017) and is based on the information provided by NWDA (2016) and MoWR (2016). The ILR links are digitised for representation only and do not represent their accurate scale. Several links are presented jointly by their planners (details in Figure 2.4)

It is estimated that the project will increase Indian irrigation potential by 25% and will also generate 34000 MW of hydro-electricity (MoWR-GOI 2016). The project, however, has an excessive cost (Jolly 2016; Koshy & Bansal 2016). The estimated

[3] The locations for intra-level ILR links are not available in the public domain. However, locations of the two intra-state ILR links studied in the present thesis are taken from their feasibility studies (NWDA 2009a; 2009b) and are presented in Figure 1.4.

cost was INR 5.6 Trillion (£68 billion)[4] in 2002-2003 which, according to the current Minister of Water Resources, River development and Ganga rejuvenation, GOI has doubled to INR 11 Trillion (£134 billion) by 2016 (Jolly 2016).

Feasibility studies for all inter-state ILR links and some intra-state ILR links are being completed by NWDA (Thatte 2006). Detailed project reports of some links are underway (NWDA 2015). The NWDA claims to address all the important concerns with IBWT links realistically in their feasibility studies; however it did not share any information until 2006 and then released only some of the reports after intervention from SCI (Pasi 2012). These reports have been critically evaluated by scholars including both supporters and critics. Supporters of ILR projects predict that the schemes will resolve several water-resources issues, most importantly the water deficit in India (Thatte 2009; Saleth 2011). On the other hand, critics persuasively raised several issues which are similar to the concerns raised at the global scale and include: the decision making and justification of water transfer (Smakhtin et al. 2007; Amarasinghe 2012), lack of transparency and public participation (Alagh et al. 2006), environmental impact, ecological disturbances (Saleth 2011), huge cost and cost-benefit distribution (Chopra 2006), potential impact of projected climate change (Bharati et al. 2011), inundation or drying up of valued land (Alagh et al. 2006), increased sedimentation and salinity (Misra et al. 2007), and resettlement and rehabilitation (Patekar & Parekh 2006; Amarasinghe 2012).

The heavy criticism resulted in a slowing of progress of the ILR projects and constantly outlined the need for improvement in the planning of these projects (Pasi 2012). The proponents of the ILR projects also agree that there are significant potential problems with the approach taken in the study and these must be addressed while operationalising the planned projects (Thatte 2006; Misra et al. 2007**;** Prabhu 2008**;** Amarasinghe & Sharma 2008; Inocencio & McCornick 2008; Jain et al. 2008). Mr Suresh Prabhu (2008)**,** chairman of the Task-force on ILR projects (2002-2004) appointed by GOI highlighted that NWDA studies have lacked

[4] Currency conversion used (dated 17.06.2017): 1 (INR) = £ 0.0121415.

a sound scientific base and transparency. He further outlined that the reports also lacked a holistic and multi-disciplinary approach which is crucial in such large-scale water resource projects. This viewpoint is supported by other scholars such as Alagh et al. (2006), Smakhtin et al. (2007) and Gupta & van der Zaag (2008) who have highlighted the need for integrated multidimensional studies based on the best practice available. Therefore, any related research could be highly beneficial for ILR projects; the projects are still in the planning phase and can accommodate changes (Alagh et al. 2006; Gupta & van der Zaag 2008; Amarasinghe & Sharma 2008; Pasi & Smardon 2012; Bandyopadhyay 2012). Keeping this context in mind, two of the intra-state levels ILR links namely Sankh-*South Koel (S-SK)* and *South Koel-Subarnarekha (SK-Sr)* which are proposed by the State Government of Jharkhand (GOJ) to connect the Brahmani-Baitarani and Subarnarekha river basins within the Jharkhand State, form the basis of this research (Figure 1.4).

The S-SK and SK-Sr ILR links are planned to function together using existing river channels; therefore, they are taken as one project in this study and are called collectively as *Sankh - South Koel - Subarnarekha (S-SK-Sr)* ILR link. The S-SK-Sr link is designed to transfer 1.79 km^3 of water per annum from the Brahmani River basin to the Subarnarekha River basin (NWDA 2009a; 2009b). The feasibility reports of both links have a similar structure and information as in the feasibility reports for the other ILR links by the NWDA; therefore, they are also prone to similar short-comings as discussed above. Moreover, Jharkhand is one of the most under-developed states in India (Mukherjee & Chakraborty 2012) with 39.1% of the population living in poverty (Government of India Planning Commission 2012). Hence, it is vulnerable to socio-economic problems being amplified by ineffective new projects. Therefore, to prevent such a situation, an in-depth multi-disciplinary study is warranted for any project being carried out here, including the ILR projects. Thus, the Sankh-South Koel-Subarnarekha (S-SK-Sr) ILR project is a suitable case study area for this research.

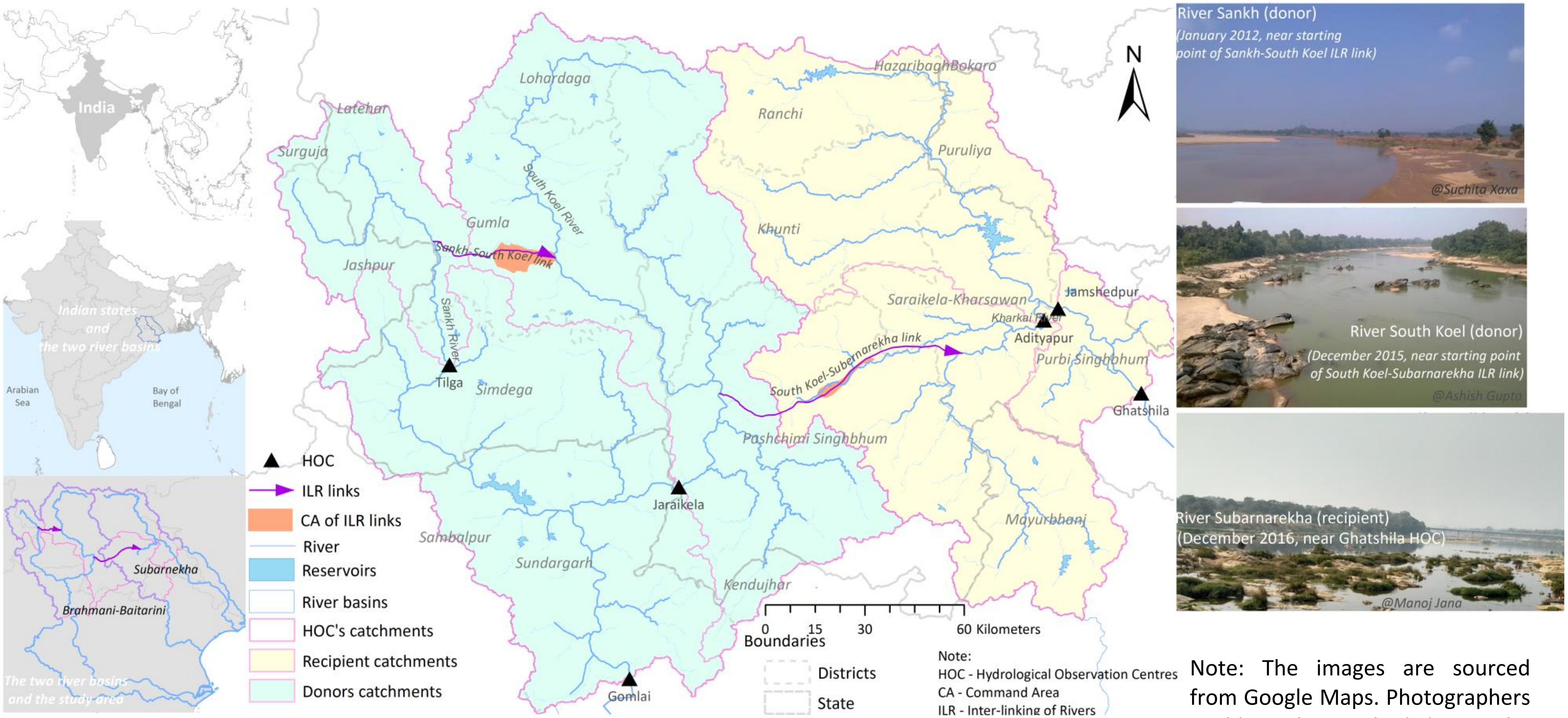


Figure 1.4: Overview of the two ILR links under study: South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) with their location in the river basins and in India.

Note: The images are sourced from Google Maps. Photographers could not be reached due to the lack of contact details; however in order to acknowledge their contribution their names have been included in the photos.

1.4 Research aim

As explored in section 1.2 and 1.3, the S-SK and SK-Sr ILR links capture many of the concerns related to IBWT management which need to be assessed through an integrated and multi-disciplinary approach as advised by scholars. Due to the hybrid and wicked nature of IBWT planning and management, it is clear that covering each and every concern of IBWT will be unrealistic. Therefore, the thesis aims:

– to evaluate the decision-making process of the Sankh-South Koel and the South Koel-Subarnarekha ILR links in India using publically accessible data and tools.

With this aim, this research attempts to address an applied problem by examining the associated theories around it. By addressing this problem, the present thesis aspires to strengthen the IBWT decision-making process in India. It will contribute to the development of a methodological tool for the fundamental IBWT decision-making on the basis of the best practices available in the field of IBWT and WRM. Thus, the objectives of this thesis are based on the best practices available; they emerge from the review and discussion of policies and practices in IBWT and WRM so far. Hence they are given in section 2.5 of Chapter 2.

As mentioned above, due to the lack of transparent, multi-disciplinary and sound scientific base, ILR planners have struggled to justify their fundamental decisions of water transfer. As most of the IRL projects, including the ones being studied in this thesis, are in the early planning phase, therefore, it is apparent that addressing the concerns related to the fundamental decision-making of the ILR projects will be highly beneficial to them. Thereby, the outcomes of this thesis could contribute substantially to the planning of the ILR projects and support their justification. Thus, the thesis attempts to address the concerns related to the fundamental decision-making process of ILR projects.

1.5 Broad description of the thesis

The structure of this thesis is as follows:

Chapter 1 briefly explains the context and challenges of IBWT projects and highlights the need for the research undertaken. It explains the case of ILR projects in India and provides an overview of the study area along with the reasons for its selection as the case study in this thesis. Further, it outlines the aim of this thesis.

Chapter 2 reviews the policies and practices in IBWT including the ILR projects so far. This review contextualises the research undertaken by explaining lineage, benefits and concerns of IBWT, outlines the gaps in planning and management of IBWT and points out the recommendations made for the best practices in the field. Further, it reviews the position of this research in the wider context of IBWT by providing a detailed synopsis of ILR projects along with the debate and uncertainties associated with it. These reviews provide a comprehensive understanding of IBWT including the ILR projects and assist in delineating the objectives of this research in order to fulfil the aim of thesis.

Chapter 3 provides details of the research approach and the materials used in this thesis. It explains the style of research covering the first objective of this thesis. It briefly describes the collection and processing of datasets as well as the tools used in this research. It also presents detailed description of the study area covering the two ILR links and the catchments involved in these water transfer projects.

Chapter 4 covers the second objective of this thesis. It characterises the important aspects of landscape as well as hydrological and socio-economic patterns in the catchments under study. The chapter adds to the understanding of the water balance patterns prevalent in these catchments, which contributes in the assessments carried out in Chapter 5 and 6 and assist in critiquing the existing plans of the two ILR links under study in Chapter 7.

Chapter 5 focuses on the third objective of the thesis and develops an integrated assessment of the water balance in the catchments involved in the water transfer projects on the basis of the best practice observed in Chapter 2. The developed appraisal is used in the simulation of ILR links and their catchments in Chapter 6. It also assists in critiquing the existing ILR plans in Chapter 7. The outcomes of this chapter provide an estimate of the prospective surplus or deficit of water in the catchments.

Chapter 6 focuses on the fourth objective of the thesis and simulates the catchments and the two ILR links using the WEAP platform under a range of current and prospective water balance scenarios covering *without* and *with water transfer*. On the basis of simulation outcomes, the chapter assesses the performances of catchments and ILR links and explains the influence of water transfer on the catchments. The outcomes of this chapter, along with the results from the previous chapters (4 and 5), are used to formulate specific advice for the two ILR links under study.

Chapter 7 critiques the existing ILR plans for the S-SK and SK-Sr links using the understanding developed from the previous chapters (4-6). Furthermore, it discusses the importance of science-supported policy used in this research covering the attributes and advantages of the research framework developed in this thesis, its transparency facilitating the indirect public engagement and its data management. Using the understanding developed, the chapter also reflects on the style of research and the complexity encountered in this doctoral research related to the hybridity and wickedness observed in the field of IBWT and WRM so far. The chapter then outlines the recommendations for the ILR projects and IBWT in general.

Chapter 8 revisits the aim and objectives of this thesis and evaluates the research undertaken. It also provides directions for the future studies in the same research field and summarises this thesis.

Chapter 2 Current understanding of Inter-basin water transfer

2.1 Introduction

This chapter explores the current status of Inter-basin Water Transfer (IBWT) and outlines the objectives of this thesis. To explore issues surrounding IBWT most effectively, a sub-set of literature has been selected at the Indian and global levels based on the themes: lineage, benefits, concerns and the best practices. This sub-set of literature comprises government-sponsored reports, peer-reviewed articles and books from different disciplines.

This literature review is structured around two elements:

1. Current understanding of IBWT-related research: The review in this level contextualises this thesis and provides the detail understanding and a critique of current studies and practices in the IBWT field.
2. The case for the Inter-linking of Rivers (ILR) projects: The review in this level positions this thesis in the bigger picture of IBWT and outlines the specific gaps addressed in this thesis.

These two elements are discussed in section 2.2 and 2.3 respectively. Section 2.4 provides a comparative picture of the ILR project and the IBWT at global scale. It is followed by the discussion of rationale and style of this research (section 2.5) and assists in delineating the objectives to achieve the aim of this thesis (section 2.6).

2.2 Contextualising the research: understanding IBWT

2.2.1 IBWT: Lineage

Water is diverted from water surplus areas to water deficit areas to ease water shortage (Golubev & Biswas 1977). Water diversion from one river basin to one or more other river basins, which are otherwise not connected hydrologically, is termed as IBWT (Gupta & van der Zaag 2008). IBWT is the widely preferred solution to overcome water deficit (Razavi Toosi & Samani 2012) and secure water supply (WWF 2007). Micklin (1984, p.37) stated that IBWT is a “purposeful rearrangement of natural hydrologic patterns via engineering works (dams, reservoirs, tunnels, pumping stations) to move water across drainage divides to satisfy perceived human needs”. Gupta & van der Zaag (2008, p.29) called it “supply-oriented engineering measures to large societal challenges” which joins ‘‘distinguished donor and recipient river basins” through “daunting engineering” structures. They found it a “fairly well established solution” for satisfying increasing water requirements and noted that it will “imply an increase of the spatial scale at which water is managed”. These projects are large and complex, and have a longer duration, often in years, to complete (Gupta & Deshpande 2004). Gichuki & McCornick (2008) and van Niekerk (2013) underline that IBWT projects are “public works” (*ibid*, p. 18) initiated and completed by governments.

Water-diversion projects have been employed for centuries (Biswas 1977; Gichuki & McCornick 2008) and their use will almost certainly continue (Shiklomanov 1999; van Niekerk 2013). The two earliest known water-transfer links are the canal connecting the Tigris and Euphrates rivers built in 2500 B.C. (Meador 1992) and the Lingqu Canal connecting the Yangtze and Pearl River basins built in 214 BC (UNESCO-WHC 2016). Several such water supply systems have been recorded by Wittfogel (1957), Vuorinen et al. (2007), Wilkinson et al. (2012) and Angelakis et al. (2012). Figure 1.1 showed that the pace of these projects accelerated in the 19th century. Most of the IBWT projects in developed countries were constructed during the first half of the 20th century; however, their pace of construction slowed down around the 1970s (Micklin 1984) which could be attributed to the emerging awareness of environmental impacts (Golubev & Biswas 1977). In contrast, after the 1970s, these projects multiplied in developing countries (Pasi 2012) which could be explained by their high population leading to increasing water use combined with their willingness to use their restricted finances optimally (Shiklomanov 1999) and the support from external funding organisations (Pasi 2012). Adverse experiences of water diversion in developed countries initiated precautionary processes and led to the international level efforts for enforcing Environmental Impact Assessment (EIA). However, developing countries lacked in EIA protocols as their related policies were at the inception stage (Hirji 1998).

Thus, the total water quantity transferred by IBWT increased from 22 km^3 per year in 1900 to 364 km^3 per year in 1986 at the global scale and is expected to at least double by 2020 (Shiklomanov 1999). These schemes are expected to affect water resource management globally, with significant impact seen in developing countries (Shiklomanov 2000). Therefore, a discussion of their benefits and concerns is warranted.

2.2.2 IBWT: Benefits, concerns and criteria

IBWT projects are driven by governing authorities who promote these projects as being critical to alleviate water deficits and to ensure water security (Wittfogel 1957; Gupta & Deshpande 2004; WWF 2007; Angelakis et al. 2012). Thus governments consider these projects highly beneficial (NWDA 2016). However, these projects are considered as a product of coalitions between politicians, engineers and financiers (Gumbo & van der Zaag 2002); thus, they continue to be one of the most contentious topics in water-resource management across the globe (Wittfogel 1957; Gupta & van der Zaag 2008; Zhang et al. 2015).

Here, while assessing the benefits of and concerns about IBWT, it is interesting to note that literature accumulated for this review showed the obvious divide of governmental vs non-governmental sources in which the former compiled benefits only, whilst the latter largely addressed concerns associated with IBWT. Extensive review of academic and non-governmental literatures reveals that only a few of them (Hirji 1998; UNESCO 1999; Ghassemi & White 2007; WWF 2007; and Gichuki & McCornick 2008) reported the benefits of IBWT projects although they have also highlighted the related concerns. Furthermore, this literature is mostly based on individual cases (IBWT projects) and there is a gap around thematic and topic-based studies. Thus, this thesis approaches the topics on a thematic basis. The following sub-sections 2.2.2.1 and 2.2.2.2 present a concise account of benefits and concerns of IBWT. The literature review also outlines a stark picture of IBWT projects by highlighting the excessive amount of criticisms these projects have attracted.

2.2.2.1 Benefits of IBWT

IBWT projects are multi-purpose in general (UNESCO 1999) and mainly built to supply water to municipalities, irrigation, industries, and hydro-electricity. Micklin (1984) and Berkoff (2003) noted irrigation is the primary reason while Shiklomanov (1999) perceived it to be municipal[1] water supply. A review of major IBWT projects across the globe (list in appendix A.1) upholds the viewpoint of Shiklomanov (1999) and points out that municipal water supply is the primary reason for the IBWT development in both developed and developing countries (Figure 2.1).

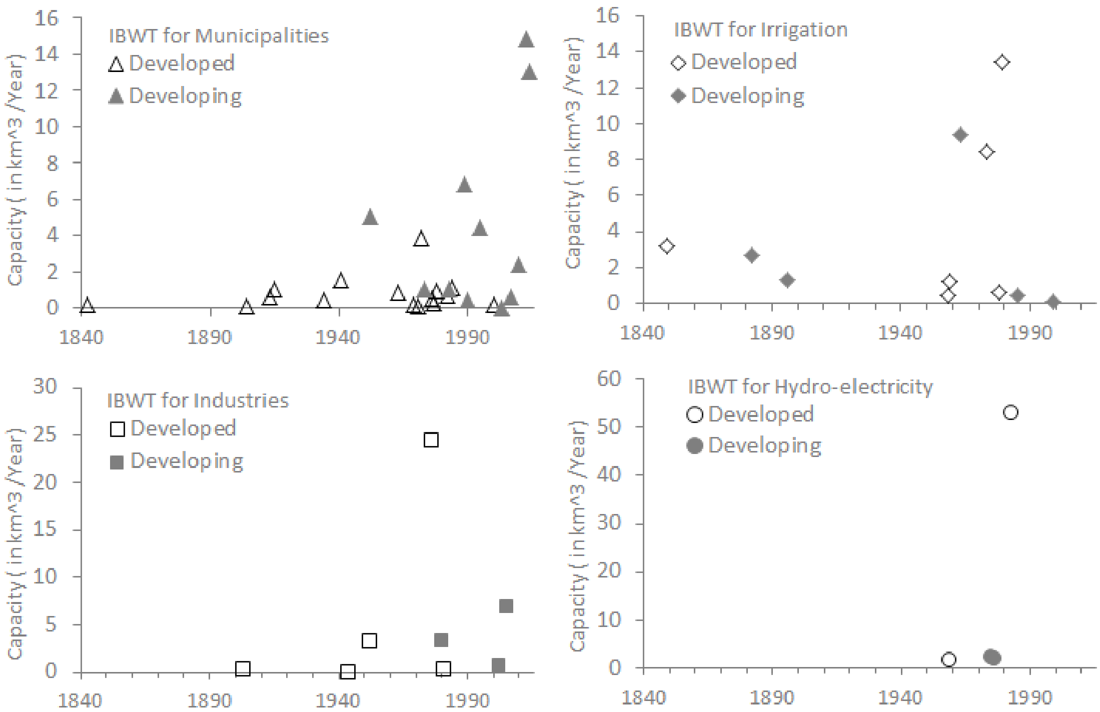


Figure 2.1: Primary purposes of major inter-basin water transfer (IBWT) projects in developed and developing countires.

Note: The capacities (km^3/year) of IBWT projects for municipalities and irrigation are similar. The capacities of IBWT projects for industries and hydro-electricity generation have largely lower capacities except couple of them (showing considerably high water transfer capacities).

[1] In this thesis, the words 'municipal' and 'domestic' are used interchangeably.

The other important purposes for these projects include water supply to irrigation, industries and hydro-power generation (Figure 2.1). However, the last two purposes for IBWT are more common in developed countries. Apart from these four major benefits, some minor benefits of IBWT projects are flow-supplementation, environmental use, recreation, flood protection and navigation (Micklin 1984; Lund & Israel 1995; Berkoff 2003; Ghassemi & White 2007; Slabbert 2007; Brekke et al. 2008; Kibiiy & Ndambuki 2015) (see appendix A.1. for examples).

Scholars have claimed that IBWT projects brought economic prosperity to many areas around the world. For instance, Gichuki & McCornick (2008) noted that these projects brought socio-economic development, allocated water for better-value use, enhanced regional equality, strengthened co-operation between donor and recipient areas and reduced deterioration of river ecosystems. Matete & Hassan (2006) found IBWT projects to be important for socio-economic development. Das (2006, p.1703) called them an “ultimate solution to alleviate water security” and important for economic development. WWF (2007) noted economic development due to the Snowy Mountains Hydroelectric Scheme. Hirji (1998) agreed reporting that the water transfer supported 25-30% of the regional economy of the recipient Murray-Darling River basin and increased flow of the two recipient rivers. He also examined the benefits from the Central Valley Project (CVP) (1937) and the State Water Project (SWP) (1960), in California, USA and asserted that these two projects improved welfare conditions in the project area. Ghassemi & White (2007) emphasised that IBWT projects have considerably promoted the overall development of many nations. Research has also highlighted the environmental improvement due to the IBWT projects. Ghassemi & White (2007) stated that the State Water Project (SWP) (1960) in California, USA helped in controlling salt-water intrusion in the Sacramento-San Joaquin delta and Suisan Marsh; resulting in improved ecological and environmental conditions. Berkoff (2003) suggested that IBWT can alleviate environmental degradation in the recipient basin; and thus he strongly supported the South–North Water Transfer Project (SNWTP) in China. Also Schumann (1999) and Kibiiy & Ndambuki (2015) observed that that many cities all over the world largely depend on IBWT for their domestic water supply. For example, Los Angeles obtains 75% of its annual water supply from the Owens Valley-Los Angeles IBWT (Hirji 1998) and Sao Paulo gets 60% of its water supply from the Sistema Cantareira project (de Andrade et al. 2011). Furthermore, Sewell (1984) and Li et al. (2013) acknowledged the role of these projects in the energy sector of Canada and China respectively.

Overall, IBWT projects have been advantageous in many areas and improved water supply of various sectors. However, these benefits have come with extensive costs ranging from financial to environmental and to social; many concerns which are discussed below.

2.2.2.2 Concerns around IBWT

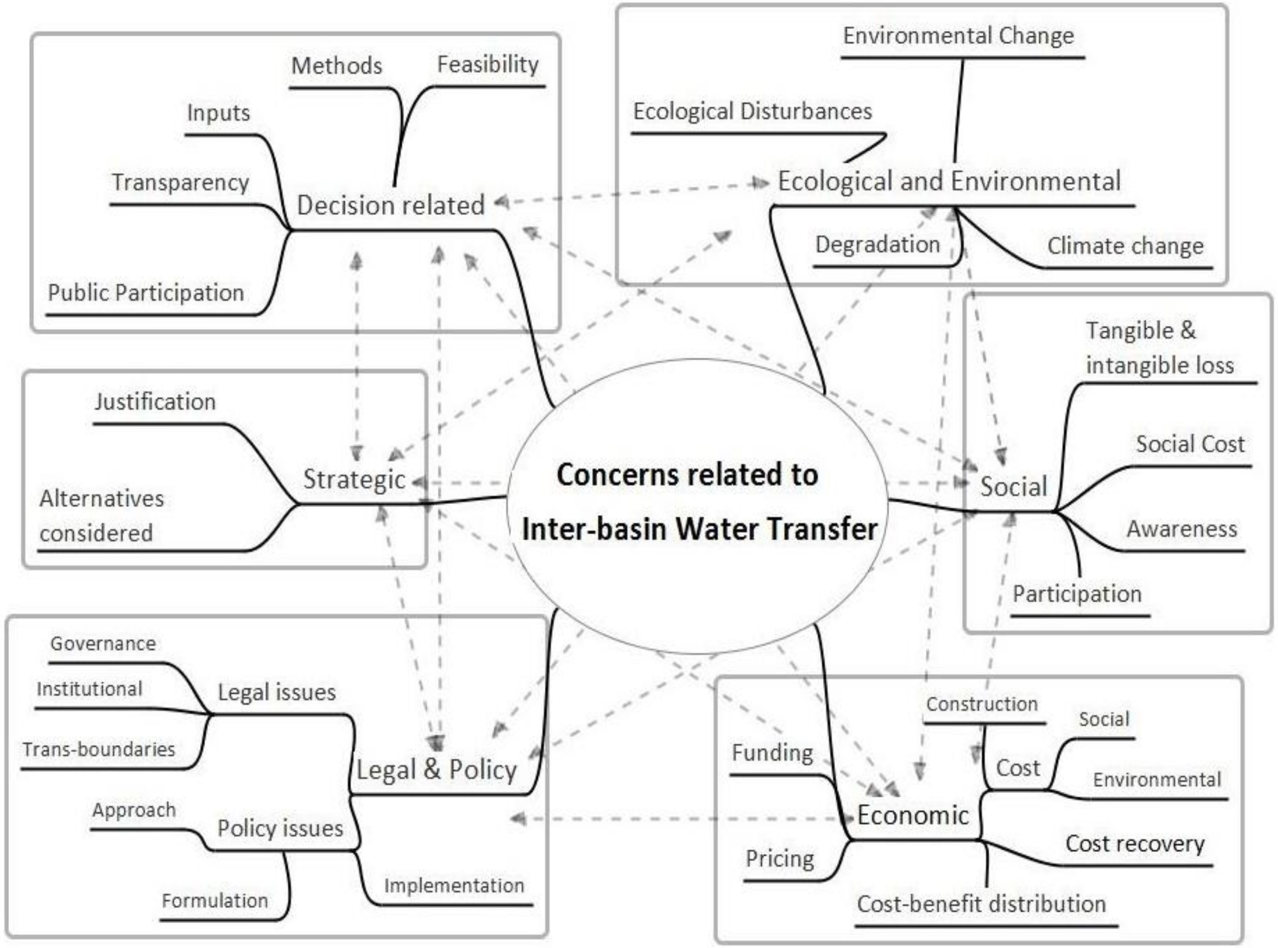
"IBWT projects and controversy proceed side by side" (Das 2006, p. 1703) and even proponents have agreed with some of the concerns raised (e.g. Berkoff 2003; Prabhu 2008). These projects prompted many queries and worries from a range of scholars and communities from different disciplines (Gupta & van der Zaag 2008). Efforts have been made to categorise them (e.g. Beattie et al. 1971; Biswas 1977; Mohile 2006; Khosla 2006; Slabbert 2007; Kibiiy & Ndambuki 2015). A detailed review of the literature suggests that the categories proposed by Khosla (2006) encompass most of the IBWT concerns. Therefore, it has been used in this present thesis to group and explain concerns about IBWT. However, some modifications have been made to include the full range of concerns raised for IBWT (Table 2.1).

Here it should be noted that these concerns interrelate with each other (Golubev & Asiliev 1977). Their interrelationships are demonstrated in the Figure 2.2 (modified after Golubev & Asiliev 1977). However, the association between and within categories and subcategories are not shown in the Figure 2.2 and have been mentioned in further sub-sections where appropriate.

Table 2.1: Categorisation[2] of concerns related to inter-basin water transfer – modified after Khosla (2006)

Category	Concerns involved
Decision related	Decision-related issues (inputs, methods, analysis, process, output, planning approach), feasibility, limitations, transparency, public participation.
Ecological and Environmental	Ecological disturbances, bio-diversity alterations, invasion of alien species, ecosystem functioning, water-quality issues, environmental changes, morphological changes, flow related concerns, climate change, environmental degradation (e.g. soil, forest, water).
Social	Displaced population, resettlement and rehabilitation, submerged land and property, health, compensation, public awareness, any other disturbance to society.
Economic	Cost related issues including social and environmental, economic evaluation of projects, cost-benefit calculation and distribution, cost recovery, pricing and funding.
Legal and Policy	Issues related to governance, institutional requirements and its efficiency, monitoring, jurisdiction, trans-boundary matters, policy, approach, theory, and attitude
Strategic	Rationale of IBWT project (e.g. irrigation requirement, drought, water deficit, high water demand, national interest), alternatives considered.

[2] Note: As cautioned by Golubev & Asiliev (1977), these categories and sub-categories interrelate and overlap with each other.



Note: To simplify the representation, efforts have been made to keep the interrelationship at categories level only.

Figure 2.2: The concerns related to IBWT projects and their interrelationships (at category i.e. first level).

i) Decision-related concerns

IBWT projects involve management of water resources for two or more basins acting as donor and recipient (Gupta & van der Zaag 2008). They include two major and convoluted components – water availability and demand (Asiliev 1977), a 'hybrid' of natural and social factors (Swyngedouw 1999), which encompasses several objectives and stakeholders (Zhang et al. 2012) with different requirements and contradictory desires (Lach et al. 2005). Thus, the IBWT decision-making process is multi-disciplinary and complicated (Gupta & van der Zaag 2008); and therefore, is wicked (Lach et al. 2005) and highly controversial (Kibiiy & Ndambuki 2015) in nature.

Evidence suggests that the complexities of IBWT decision processes make these projects prone to a chain of inconsistencies in their planning and management. The irregularities include wrong or misinformed assumptions (de Andrade et al. 2011), incorrect inputs (Micklin 1984; Gichuki & McCornick 2008), and scale issues related to spatial (Gupta & van der Zaag 2008) and temporal (Smakhtin et al. 2007) resolutions which lead to inaccurate assessment of water availability (WA) (Micklin 1984) and water demand (WD) (Liu & Ma 1983) at both the annual and seasonal levels (Smakhtin et al. 2008; Li et al. 2014). In some cases, WD is valued inequitably among the different WD sectors (Hirji 1998) as well as across different regions (Alagh et al. 2006). These discrepancies in WA and WD cause under- or over-estimation of the water balance in the catchments of the IBWT projects (Liu & Ma 1983; Micklin 1984) and undermines the reliability of the water transfer decisions made (Krueger et al. 2007). Further, the influence of climate changes on WA in the catchments is significant (Menzel & Burger 2002) and affects the IBWT projects too (Cosens 2010). This influence has been explored in developed countries during current IBWT planning and management (e.g. Brekke et al. 2008); however, developing countries are far behind in such exploration (Maknoon et al. 2012) that undermines the IBWT decisions made in these countries. Additionally, the risk and vulnerability assessments of these water transfer projects (Jain et al. 2005; Gohari et al. 2013) as well as the sustainable development of the catchments involved in the project (Johnson et al. 2007; Gupta & van der Zaag 2008) have also been overlooked (Kibiiy & Ndambuki 2015).

On the other hand, the IBWT decision process contains challenges related to data management such as data collection, processing and compilation on a coherent basis (Narain 2000), scientific bases and technological possibilities (Gupta & van der Zaag 2008), all still evolving in developing countries (Sokolov & Chapman 1974; Matondo 2002). Therefore, IBWT planners in these countries use traditional methods for the planning and management of these projects which are outdated and undermine the confidence in the decisions made (WCD 2000).

Furthermore, these projects are wicked and thus constantly require transparency and collective participation of all stakeholders in their planning and management (Lund 2012) promoting data democratisation in line with The Dublin Principles (Solanes & Gonzalez-Villarreal 2009). However the IBWT decision-making process suffers from a lack of transparency and public participation (Islar & Boda 2014) together with minimal efforts for public awareness (Bruch et al. 2005), significantly observed in developing countries (Matondo 2002). It diminishes the credibility of water transfer decisions made (Kidd & Quinn 2005; Ghassemi & White 2007), instigates misinformation and conflicts which eventually stall these projects (Gumbo & Van Der Zaag 2002; Blatter et al. 2009).

Further, IBWT projects follow the supply-side approach (Gupta & van der Zaag 2008). This approach has been challenged extensively and instead integrated approach has been promoted (Loucks et al. 2005); however, the former is still preferred in developing countries (WCD 2000; D'Souza 2003). Moreover, IBWT planners put a large emphasis on the technical side of the projects, especially in developing countries (Matondo 2002) and ignore other vital factors such as environmental, social and economic issues which lead to several legal and strategic concerns.

As a result of these inconsistencies, information related to IBWT projects are often distorted and fuels related conflicts (Micklin 1984; Gichuki & McCornick 2008), which is a significant problem in developing countries (Matondo 2002). Thus the benefits from IBWT projects are undermined which deters its stakeholders (Gichuki & McCornick 2008).

ii) Ecological and Environmental Concerns

The ecological and environmental concerns about IBWT projects are amongst the most prominent and persistent (Quinn 1968; Micklin 1984; Meador 1992; Das 2006; Baggett 2009; Cosens 2010) and have laid foundation for several legal actions and caused changes in policies (Hirji 1998). These concerns are significantly related to the IBWT decision-making process (Figure 2.1) and can result in irreversible environmental impacts (Howe & Easter 1971; Gichuki & Mccornick 2008).

A major challenge for IBWT planning is to maintain the environmental flow in the donor river basins (Li et al. 2015). If these projects are not properly planned, schemes could violate the limit of minimum environmental flow in the donor river (Smakhtin et al. 2007). In some cases, they have drastically changed the natural flow of the donor river (Hirji 1998) and later on efforts have been made to restore the flow which challenges the rationale of IBWT in the first place and adds extra costs (Ghassemi & White 2007). Further, the low flow in donor rivers due to the IBWT projects can affect its downstream morphology (McCully 2001), dry up wetlands (Richter et al. 2010) and trigger delta retreat in the donor basin which leads to sea-water incursion. (Pittock et al. 2009; Zhang 2009). On the other hand in recipient basin, these projects promote wasteful use (Quinn 1968; Albiac et al. 2003) which cause water-logging (Singh 2002), salinization (Iyer 1998; McCully 2001) ecological and environmental problems in the recipient basin (Hirji 1998).

IBWT projects change the capacity of sediment transportation in rivers which can affect their erosional and depositional powers (Hey 1986), resulting in problems such as undermining the infrastructure, low water-quality and siltation of spawning grounds (Pittock et al. 2009; Kibiiy & Ndambuki 2015). By altering the flow regime, these projects cause ecological changes (Daniels 2004; Li et al. 2013), which adversely affect bio-diversity of donor as well as recipient river basins (McCully 2001; Snaddon & Davies 2006) and jeopardise their ecological resources (Matete & Hassan 2006). Transfer of water from one river to another could also transport pollution; it will therefore need treatment before use (Cosens 2010). IBWT could introduce alien species to the recipient river (Daniels, 2004; Das 2006), and cause other ecological concerns related to the storage structures of these projects such as thermal stratification, eutrophication, change in chemical composition and greenhouse-gas emissions from its reservoirs (McCully 2001; Daniels 2004; Das 2006; Lakra et al. 2011).

Additionally, evidence suggests that these projects affected the surface and ground WA downstream of the donor basin (Baggett 2009) leading to problems such as drying up of lakes (Hirji 1998) and water-allocation conflicts (Madhusoodhanan & Eldho 2012).

iii) Social Concerns

IBWT projects have substantial social costs (WWF 2007) despite the debated benefits (Berkoff 2003) which are unequivocally related to the concerns mentioned previously (Figure 2.1). They include commensurable and incommensurable costs covering resettlement and rehabilitation of population affected by these projects.

IBWT projects consider only commensurable costs in the planning phase (Patekar & Parekh 2006). These costs mainly include resettlement and rehabilitation of people by dams and other water resource infrastructure (McCully 2001). These projects physically uproot “large sections of people from their land, economy, resources and culture” (Singh 2002, p.182) and then controversially resettle them (WCD 2000). Thus, displacement and resettlement are massive problems for IBWT projects or any large-scale water resource project (Berkoff 2003); these problems are further aggravated by their mismanagement (WCD 2000; Patekar & Parekh 2006). Singh (1997) and McCully (2001) provide several strands of evidence in this regard. Das (2006) underlined that IBWT projects in Canada displaced native people and the same has been noted by Patekar & Parekh (2006) in the case of India. McCully (2001) gave a conservative estimate that 2.2 million people have been displaced by 134 dams completed across several countries, excluding India and China. He further outlined that this figure could exceed the population of the United Kingdom, if the number of people displaced in China are included in this estimate. Furthermore, these costs increase substantially when they are considered after the construction of a project (Cosens 2010).

On the other hand, several incommensurable costs such as emotional, cultural and livelihood loss, and loss of valued land via submergence have been neglected by the planners of IBWT and other large-scale water resource projects (McCully 2001; Singh 2002). These costs pose serious limitations to IBWT or any water resource projects (Blatter et al. 2009).

Furthermore, people affected by IBWT projects who could be mostly from low-income strata and hence more vulnerable communities (Matete & Hassan 2006) are expected to sacrifice their interests in the name of the public good by surrendering their rights to land and water (Singh 2002; McCully 2001; Patekar & Parekh 2006). Often they are not well compensated, especially in developing countries (WCD 2000). Such issues ignite local opposition (McCulloch 2006) which grows powerful if not addressed and can stall the progress of IBWT projects (Cosens 2010) and can continue even after the completion of these projects (de Andrade et al. 2011). Moreover, the concept of sacrifice for national interest may change in the future with governments forced to take care of local environmental and social needs as seen in the Pyramid Lake Litigation related to Truckee-Carson IBWT Project (Cosens 2010).

Besides, IBWT projects could stimulate social disputes in their catchments and promote inequitable use (Pittock et al. 2009). People from the donor basin who are dependent on the river for their livelihood suffer to a great extent while people in the recipient basin are generally benefitted by IBWT projects (Bhattarai et al. 2005). This disturbs and/or exacerbates the economic balance (Feldman 2001) and instigates social and political conflicts (Gleick 1988; WWF 2007; Cosens 2010).

iv) Economic Concerns

There is no ambiguity about the high cost of IBWT projects among its proponents and critics (Berkoff 2003; Gupta & van der Zaag 2008). Supporters argue that the high cost is justifiable as IBWT projects bring prosperity as seen in many cases across the globe (Seastone & Hartman 1963; Muller 1999); however, critics disagree arguing that the massive cost of these projects puts excessive pressure on public funds (Cosens 2010) and is difficult to recover (Yang & Zehnder 2005) or justify by the benefits from these projects (Berkoff 2003).

Often, by the time the project is implemented, the cost multiplies several times (Gupta & van der Zaag 2008) due to the slow progress of IBWT projects (Smakhtin et al. 2008) as a result of the several issues which are discussed in previous sections (Figure 2.2). The increasing cost of these IBWT schemes could make the water transferred unaffordable to its beneficiaries and thus adversely affect the demand of transferred water (Yang & Zehnder 2005). If beneficiaries are asked to fund IBWT projects, these projects are less likely to be commenced at all (Howe 1977).

On the other hand, IBWT planners are criticised for favouring irrigated agriculture, which is usually the largest shareholder of transferred water (Figure 2.1) with the highest consumption (Micklin 1984). Also, irrigation is often subsidised (Muller 1999) and therefore it obtains an under-priced water supply which leads to even higher water consumption (Albiac-Murillo et al. 2003). This results in inefficient water use (Bandyopadhyay 2012) and thus encourages high water demand once again (Gohari et al. 2013). Additionally, due to the subsidies, the agriculture sector is unable to cover the cost of the water transferred to it by the IBWT projects. This situation is further aggravated by growing low-valued crops and over-production leading to lower prices for crops (Howe 1977; WWF 2007). Thus the burden to pay for the transferred water falls onto other stakeholders which leads to the inequitable cost distribution among different stakeholders of the IBWT projects (Gupta & van der Zaag 2008). Another important conern of these projects is unbalanced distribution of benefit among donor and recipeint catchments which provokes socio-political conflicts (Getches 2005; Gichuki & McCornick 2008).

Additionally, IBWT planners have been condemned for weak economic evaluation of the projects (Albiac-Murillo et al. 2003) resulting in the underestimation of total cost (McCulloch 2006). Further, as menitoned in previous sections, IBWT planners are criticised for ignoring environmental and social cost in IBWT planning (Fisher

1977; Chopra 2006; Matete & Hassan 2006) resulting in additional costs to the IBWT projects at a later stage (Ghassemi & White 2007; Cosens 2010).

v) Legal and Policy Concerns

When IBWT projects cross multiple jurisdictions, they stimulate various disagreements among stakeholders regarding almost all of the other IBWT concerns as a result of their interrelationships (Figure 2.2). The agreement between all stakeholders entails understanding and harmony between all the parties involved which is difficult (Ghassemi & White 2007). Further complications arise when international legal aspects are involved (Biswas 1977; Marquette & Petterson 2009) as law and policies related to IBWT projects often vary from states to countries as per their needs (Lund & Israel 1995) and, could be misused (Klein 2007). Moreover, the IBWT planners substantially influence the perspective and substance of these projects according to their own preferences which clashes with different stakeholders (Lund & Israel 1995) and makes the mutually acceptable legal agreements difficult to achieve among all stakeholders (WCD 2000).

Globally, in general, water is within state or local government jurisdiction (Micklin 1984; Narain 2000). However, IBWT projects are mostly planned and manged by National/federal/Central governments (Micklin 1984; Albiac et al. 2003; Gichuki & Mccornick 2008; NWDA 2016). These governments enjoy prerogative powers in this regard; however, state governments also play an important role in the interstate IBWT projects (Micklin 1984; NWDA 2016). The different layers of governance lead to institutional, legal and political complexities (Micklin 1984) which are further entangled by the trans-boundary issues (Biswas 1977; Beaumont 2009; Ahmed 2012).

Further, although several impacts of these projects initiate the formulation of related law or policy (Klein 2007; Cosens 2010), the process is slow in developing countries (Hirji 1998) which is due to the institutional inefficiencies (Bhattarai et al. 2002; Gichuki & Mccornick 2008) and the prevailing corruption (Gichuki & McCornick 2008). Also, the lack of appropriate mechanism makes the implementation of relevant legal acts and polices challenging in developing countries (Patekar & Parekh 2006).

Further, long-term water transfers get more stringent legal and economic scrutiny than short-term water transfers by the IBWT planners which escalate the cost and cause delay in their progress, forcing the IBWT planner to withdraw (Lund & Israel 1995). On the other hand, legal contracts underpinning IBWT could allow their planners to undermine prevailing water rights in the project area, igniting political and legal conflicts (Lund & Israel 1995). These conflicts discourage data availability in the public domain (Biggs et al. 2007), undermining The Dublin Principles (WMO 2017; Solanes & Gonzalez-Villarreal 2009). Additionally, IBWT plans can lack in consistency with other developmental policies prevalent in the region and thus could overlap with others and be less effective (Chopra 2006).

vi) Strategic Concerns

IBWT projects are warranted as a critical solution for the water deficit regions (Islar & Boda 2014) in both naturally as well as demand-driven water deficit cases (Kibiiy & Ndambuki 2015). Cox (1999) asserted that these projects should be carried out only after exploiting all demand-management options; however, this is not the case as underlined by Gumbo & van der Zaag (2002). Most of the IBWT decisions are heavily influenced by politics (Gumbo & Van Der Zaag 2002) which prompts the concerns related to IBWT decision-making (Pasi 2012) due to their interrelationships (Figure 2.2). Additionally, IBWT decisions could be influenced by social and environmental arguments rather than the cost and benefit of these projects (Berkoff 2003). However, Gumbo & van der Zaag (2002, p.811) outlined that the "powerful coalition" of "engineers, financiers and politicians", which dominates IBWT projects, supports the supply-side solutions over the demand-side ones due to their own ambitions and management ease. Policy makers frame IBWT projects as signs of modernity, development and economic growth and therefore often these schemes are used to gain political benefits (Pasi 2012; Islar & Boda 2014). Thus IBWT projects are not always a true solution for the water deficit (Gumbo & Van Der Zaag 2002).

Further, while justifying these projects, IBWT planners are frequently condemned for being authoritative and secretive due to the lack of transparency and public participation in their decision-making (UNESCO 1999; Thakkar & Chaturvedi 2006). Remarkably they often justify these projects as 'in the national interest' to fulfil WD (Gleick 1988; Pittock et al. 2009; NWDA 2016b). However, the notion of 'national interest' can be challenged as a result of growing environmental and social awareness and thus local needs can be preferred instead of the national interest, as seen in case of Truckee-Carson IBWT Project i.e. Pyramid lake litigation (Cosens 2010). IBWT projects are also justified on the basis of high water demand in the recipient area (Ghassemi & White 2007). However, Berkoff (2003) and Gohari et al. (2013) pointed out that the supplemented water supply from other basins encourage inefficient use of water in the recipient basin and could lead to elevated water demand in it.

On the other hand, growing evidence suggests that the assertions made by these big water-resource projects are overrated in many cases (Singh 2002); some IBWT projects did not fulfil the claims they made (McCully 2001), while in some cases, these projects were actually not needed (McCulloch 2006).

2.2.3 Critiquing benefits and concerns: advice for IBWT

IBWT projects are multi-purpose projects primarily built for municipal, irrigation, industrial needs and hydro-power generation (UNESCO 1999). They have brought prosperity to many areas around the world; however, their planning and management is a conundrum (Ghassemi & White 2007). They are lauded for alleviating water scarcity (Das 2006), allocating water to better-value use (Gichuki & McCornick 2008) and fulfilling environmental needs in the recipient basin (Berkoff 2003). However, they also face significant criticism for their planning process (Gupta & van der Zaag 2008) along with several concerns raised regarding their environmental (Snaddon & Davies 2006), social (McCully 2001) and economic (Yang & Zehnder 2005) impacts. The IBWT planners also struggle in facing legal and policy (Marquette & Petterson 2009) challenges and are criticised for their strategic approach (Cosens 2010).

Like other large-scale WRM projects, the IBWT projects are known as wicked problems (Lach et al. 2005) and thus, they require careful planning based on sound science covering multiple disciplines (Lund & Israel 1995). Due to their convoluted nature, IBWT projects are advised to use extensive and reliable data (Beattie et al. 1971; Gourdji et al. 2008) with refined resolution (Smakhtin et al. 2007), state-of-the-art methods and tools (Jain et al. 2008) along with a range of expertise needed for the planning (Loucks et al. 2005). The IBWT planners should ensure the sustainable development of the catchments involved in the project (Gupta & van der Zaag 2008). It is essential to know that the donor basin is self-sufficient in meeting its current and future water needs, and that the recipient basin has critical WD that exceeds the WA from all possible alternatives within the basin (Kibiiy & Ndambuki 2015). As these projects involve different stakeholders with conflicting requirements, they require an integrated and transparent approach (Marquette & Petterson 2009) facilitating public participation (Lund 2012). Raising public awareness (Feldman 2001) reduces possibilities of conflicts (Bruch et al. 2005) and facilitates smooth planning and management of IBWT projects (de Andrade et al. 2011) ensuring the sustainability of IBWT projects (Gichuki & Mccornick 2008).

Further, IBWT projects must address the ecological and environmental concerns in both donor and recipient basins (Matete & Hassan 2006) for which a thorough environmental impact assessment (EIA) is required (Kidd & Quinn 2005) which must be carried out before the final decision of implementing water transfer is made (Cosens 2010). Also, detailed studies identifying the social impacts of the IBWT project must be carried out (Kittinger et al. 2009) and mitigation plans must be made, discussed and agreed up front (Patekar & Parekh 2006; Cosens 2010) covering ways to provide justified compensation to the affected population (Krueger & Segovia 2008). Further, a detailed economic evaluation of IBWT projects covering all costs including the environmental and social costs, must be carried out in advance (Howe & Easter 1971; Lund & Israel 1995) which should also cover cost-recovery (UNESCO 1999), equitable cost and benefit distribution (Bhattarai et al. 2005) and justifiable pricing (Ballestero 2004). Furthermore, the need for transparent and accountable institutional infrastructures (WCD 2000) by the IBWT projects: to make informed policy related to the project (Prabhu 2008) and to raise awareness regarding the project (Feldman 2001), should be made beforehand. Such practices support the smooth functioning of IBWT projects (or any WRM project) (Loucks et al. 2005) and allow sustainable development for all stakeholders involved in the project (Gohari et al. 2013; WMO 2017).

These efforts, advised for the planning and management of IBWT projects, will assist the IBWT planner in justifying their decisions (Gumbo & van der Zaag 2002). Based on these efforts, scholars have constantly tried to delineate the criteria-sets for the evaluation of IBWT projects in order to justify them (Cox 1999; Kibiiy & Ndambuki 2015).

2.2.4 Criteria-sets for IBWT

The increasing trend to implement IBWT projects across the globe and the ensuing concerns has attracted scholars to evaluate them (Kibiiy & Ndambuki 2015) as "each IBWT proposal needs thorough evaluation to determine if it is justified or whether it should be prohibited" (Cox 1999, p.173). Several criteria-sets have been proposed to evaluate these projects (Gupta & van der Zaag 2008).

In 1978, the *International Commission of Irrigation and Drainage (ICID)* defined one of the first criteria-sets for IBWT (cited in Rahman 1999, p. 86) which is as follows:

1. The donor basin must have surplus water after fulfilling all its needs, and its current and future water requirements must be secured before implementing IBWT.
2. The recipient basin must have a water deficit after deducting water available:
    2.1. Through all possible alternative sources which are cheaper than IBWT, and
    2.2. By saving available water through effective management without affecting the productivity.
3. Adverse impacts of the water transfer are minimised.

In 1999, *W. E. Cox* proposed a more comprehensive criteria-set (Cox 1999, p. 173) for the evaluation of IBWT projects which are as follows:

1. The recipient basin must encounter substantial water deficit in present or in future after deducting its:
    1.1. Natural WA, and
    1.2. Possible WA through WD management.
2. The donor basin must not encounter water deficit in the present or in the future due to the water transfer and IBWT project must not significantly hinder its future economic development. However, the donor basin can consider transferring water in the case of obtaining compensation in lieu of its productivity loss.
3. A thorough EIA must be carried out for donor and recipient basins to ensure that the project will not adversely affect the environment. However, a project can be considered if it is ready to compensate for the environmental damage.
4. A detailed evaluation of social and cultural influence is required to guarantee that the project will not cause any significant interruption. However, projects can be considered if they are ready to compensate for any potential loss.
5. The net benefits from the water transfer must be shared impartially between donor and recipient basins.

In 2008, *J. Gupta and P. van der Zaag* reviewed the available IBWT criteria-sets (Gupta & van der Zaag 2008, p.32) and summarised them using principles IWRM. However this set did not explicitly include EIA as part of the principles. They are as follows:

1. The donor basin should have real surplus water while the recipient basin should have a real water deficit after efficient water use is available there.
2. The IBWT project should be socially, environmentally and economically sustainable and should be adaptive to natural and social stress.
3. The IBWT project should be planned under good governance practice.
4. The project should balance the existing rights of territory of the project with the needs of the project.
5. The IBWT project should be based on sound science including hydrological, ecological and socio-economic analyses which should identify associated risks, uncertainties and any knowledge gaps. All alternatives should be considered.

In 2015, *J. Kibiiy and J. Ndambuki* proposed a simpler criteria-set (Kibiiy & Ndambuki 2015, p.124) based on an adaptable approach based on three conditions:

1. Justification of the need for water transfer
2. Demonstration of minimising the anticipated negative impacts
3. Demonstration of maximising the anticipated positive impacts

These three basic requirements share equal weight and can unfold into sub-branches (next level) as required. Those sub-branches can unfurl further at different levels as needed and will have the same weighting within the branch or sub-branch and so on. Each branch or sub-branch justifying the IBWT project will be marked positive and *vice versa*. The final rating for the IBWT project will be based on the total sum of all positive and negative marks. Kibiiy & Ndambuki (2015) mentioned that this approach of criteria-branching can be built using any acceptable guidelines.

The criteria-sets already discussed vary in their approach towards justifying IBWT projects; however, they all have the following common features:

1. The donor basin must have surplus WA after fulfilling all its present and future WD.
2. The recipient basin must have a water deficit after tapping all possibilities of WA within the basin.

Additionally, criteria-sets put emphasis on detailed study covering multi-disciplinary aspects of IBWT projects using sound science and an integrated approach in order to minimise the adverse impacts of projects and maximise the benefits and its equitable distribution among donor and recipient basins; IBWT project and its catchments should be sustainable.

Amongst all criteria-sets discussed, the first three (ICID cited in Rahman 1999, p. 86; Cox 1999; and Gupta & van der Zaag 2008) are very similar and follow relatively specific procedures. The fourth criteria-set by Kibiiy & Ndambuki (2015) slightly differs and proposes IBWT criteria sets with flexible requirements. However, the flexibility to select the IBWT requirements could be heavily biased which is alarming given the already established influence of the dominant partnership of “engineers, financiers and politicians” (Gumbo & van der Zaag 2002, p.811). The criteria-set proposed by Cox (1999) has been the most widely used and applauded by scholars (Bruk 2001; Pittock et al. 2009).

The above discussion of benefits and concerns provides a detailed understanding and a critique of the current research and practices in the IBWT field including a review of the available criteria-set for the evaluation of IBWT projects. After this discussion, the present literature review proceeds to critique the specific case studies used in the present thesis.

2.3 The case of Inter-linking of Rivers projects in India

As mentioned in chapter 1, this thesis takes two IBWT links of the proposed Inter-linking of Rivers (ILR) projects in India as its case study. Therefore, it is essential to understand the current status of ILR projects including their: overview (section 2.3.1) covering development history, details and the elements of existing ILR plans and the associated debate covering discussions of projected benefits and existing reservations made.

2.3.1 ILR: the Project overview

2.3.1.1 Development history

India receives ample rainfall at the national level; however, its unequal spatio-temporal distribution[3], due to the complex tropical monsoon system and topographical restrictions, causes concurrent flooding and drought in the country (Bansil 2004; Gaur & Amerasinghe 2011) leading to enormous hardships for the people affected (NWDA 2016a). On the other hand, being a rapidly developing economy with a rampantly growing population, the country is facing increasing

[3] Due to the monsoon cycle, it gets its major portion of rainfall in the monsoon season (June-September). Further, 71% of Indian water resources are located in 36% of its total area (Bandyopadhyay & Perveen 2006).

water demand from various users (Mall et al. 2006). Furthermore, GOI claims that by 2050 conventional irrigation sources will not be sufficient to fulfil food requirements (NWDA 2016). Thus, as a solution to all these problems, several IBWT projects collectively known as ILR projects in India are being planned by the Government of India (GOI) under the supervision of the National Water Development Agency (NWDA) (NWDA 2016a). A brief time-line showing important events of this planning is given in Figure 2.3.

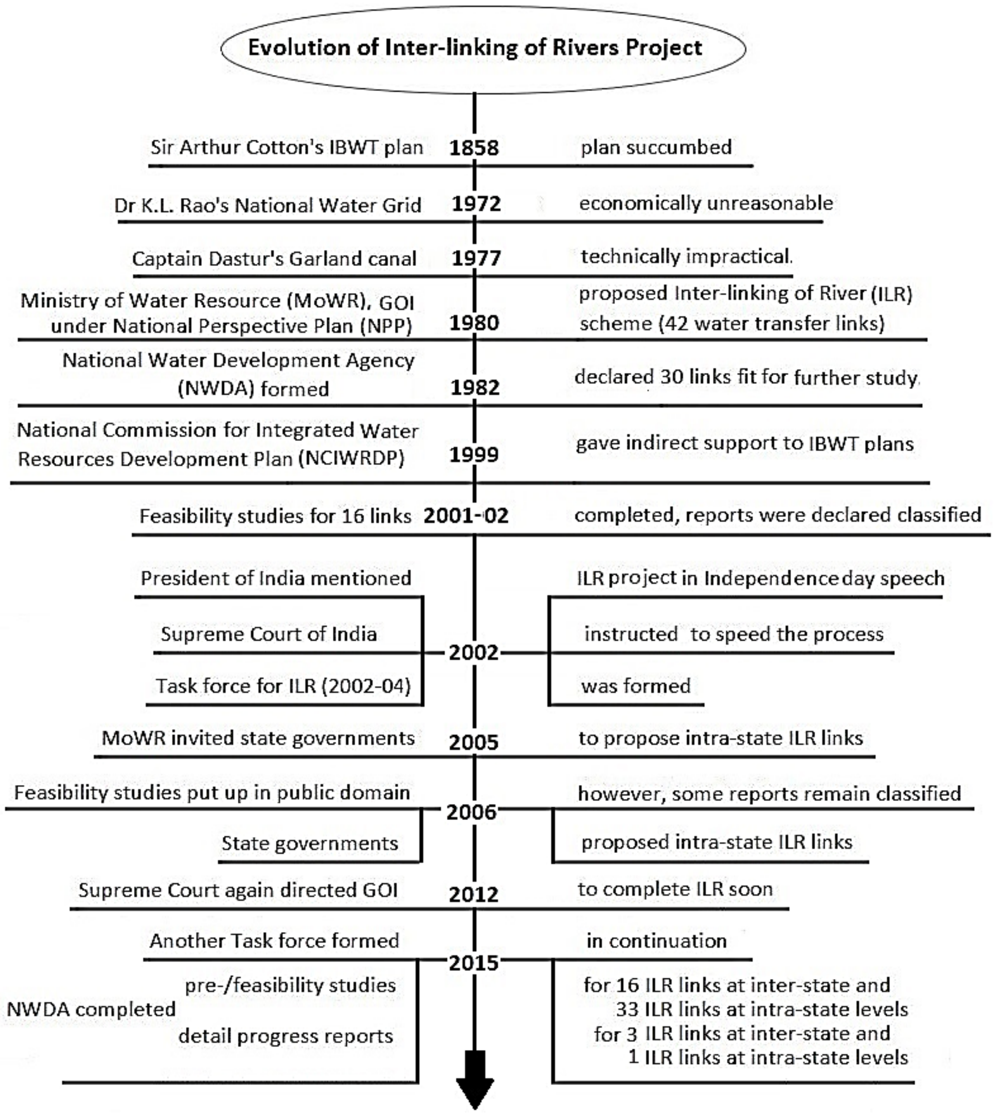


Figure 2.3: Inter-linking of Rivers (ILR) project, India - a time line.

As seen in Figure 2.3, the roots of ILR projects are in Colonial India (D'Souza 2003). The British military engineer Sir Arthur Cotton was the first to propose an IBWT plan to navigate from Karachi to Kolkata then to Chennai in 1858; however, the plan succumbed to financial problems (Headrick 1988, p. 181-182). After independence, a phase of dam building[4] began in India (Singh 2002; Radhakrishna 2003) and two IWBT plans were proposed; the National Water Grid by Dr K.L. Rao in 1972 (Rao 1979, p. 223-232) and the Garland Canal by Captain Dinshaw Dastur in 1977 (NWDA 2016b). The costs of Dr Rao's plan were found to be significantly underestimated and economically unreasonable by the Central Water Commission (CWC) and Captain Dastur's plan was found to be technically impractical by CWC and other experts (NWDA 2017).

In 1980, under the National Perspective Plan (NPP), the Ministry of Water Resource (MoWR)[5] of GOI proposed another IBWT scheme (Alley 2004) with 42 water-transfer links to transfer water from surplus basins in northern India to deficit basins in southern India (Pasi 2012). In 1982, MoWR formed an autonomous body, NWDA, to study, survey and investigate the feasibility of those links (NWDA 2016b). The NWDA identified only 30 water-transfer links fit for investigation (Figure 2.4) and grouped them in two major components: Himalayan (14 ILR links) and Peninsular (16 ILR links) components (NWDA 2017) according to their regional distributions (Prasad 2004).

In 1999, another government institution, the National Commission for Integrated Water Resources Development Plan (NCIWRDP) insisted that the irrigation potential of the country needed to be expanded by exploring new water resources in order to meet the potential food demand by 2050; it thus gave its indirect support to the ILR project and helped NWDA to justify the project (Amarasinghe & Sharma 2008). By 2001-2002, NWDA claimed complete feasibility of 16 ILR links (Pasi 2012; Alley 2004), however these reports were "classified and off-limits to all citizens except the highest ministry and government personnel" (Alley 2004, p. 216). Thus, the plans for ILR projects or any information related to them were not available to the public and GOI maintained a low profile (Shukla & Asthana 2005).

[4] As per World Commission on Dams (WCD) (2000), India is among the top five countries for building dams.
[5] The Ministry of Water Resource was then known as Ministry of Irrigation.

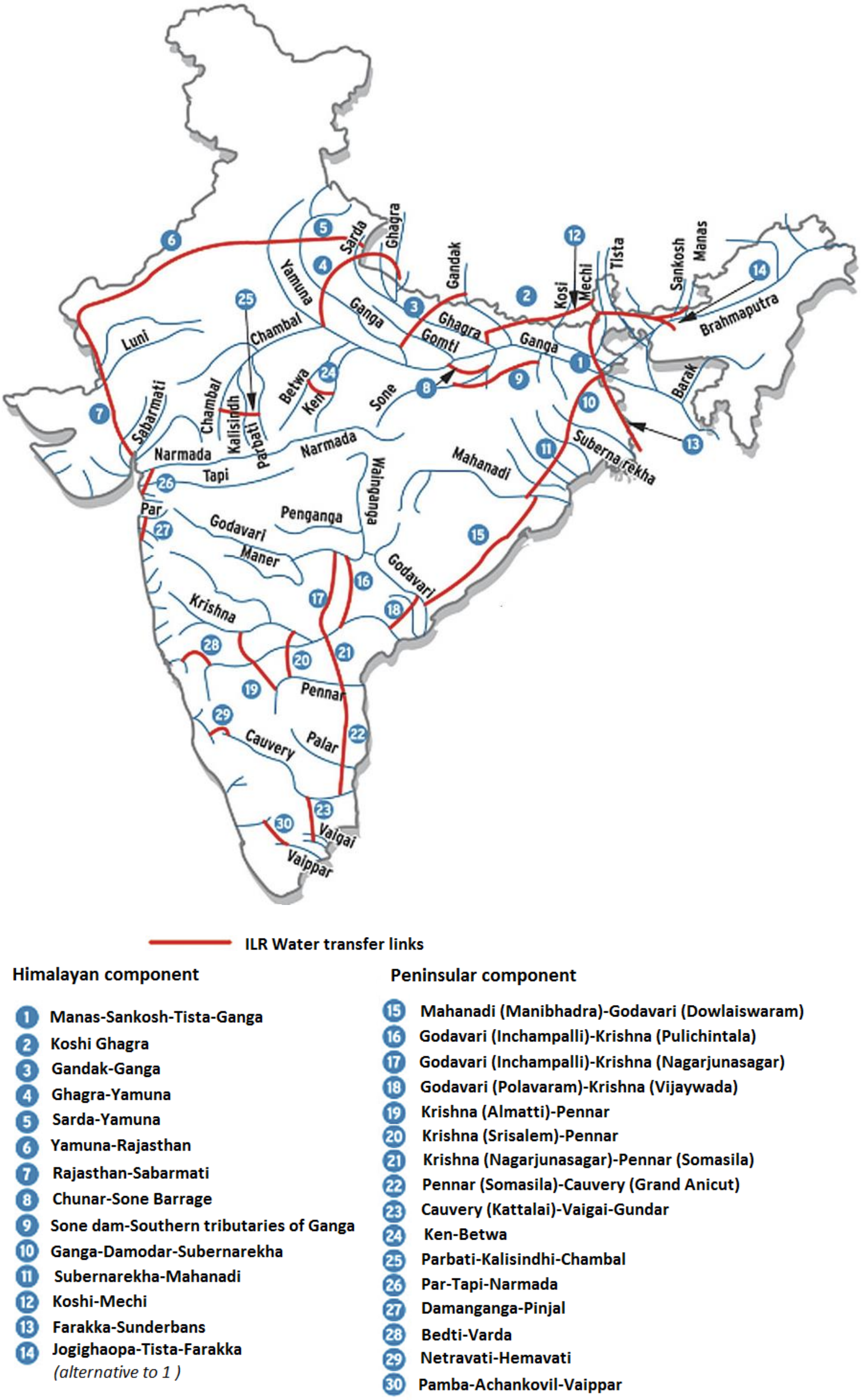


Figure 2.4: Inter-linking of Rivers (ILR) Project: Himalayan and Peninsular Components (Source: MoWR 2016).

ILR came to the fore suddenly in 2002 when the President of India mentioned it in his Independence Day speech (Iyer 2012) and soon after the Supreme Court of India (SCI) directed GOI to speed up the project evaluation (Alley 2004; Pasi & Smardon 2012) and complete it in 10 years' time (Iyer 2002). This started a chain reaction and a task-force (2002-2004) was formed to draw up action plans for ILR and speed-up the process (D'Souza 2003; NWDA 2017). A passionate debate between proponents (mostly from government) and opponents (mostly non-government) followed (Pasi 2012) and demands to put reports into the public domain were made (Alley 2004). In April 2006, following further instruction from the SCI, feasibility studies of some links were put into the public domain via NWDA's official website (Pasi 2012); however, GOI maintained classified status on some links such as ILR links of the Himalayan Component without citing any reason (Alagh et al. 2006).

In the meantime during 2005-2006, GOI invited state governments to propose water transfer links within their states (NWDA 2017). Several states developed proposals (Figure 2.5) and NWDA was given responsibility to check their feasibility (NWDA 2017). Nevertheless, the debate between proponents and opponents continued and was boosted by another order from the Supreme Court in 2012 (Amarasinghe 2012) and then after by formation of the current government[6] (Mohan 2014; Jolly & Probe International 2016). Another task force was constituted by the current GOI in 2015 (MoWR-GOI 2016). The task force is in the process of consultation with state governments and experts (NWDA 2016b).

2.3.1.2 Details

The ILR projects are an interconnected series of IBWT links (hereafter called ILR links in the Indian case) (Iyer 2012). The estimated cost was INR 5.6 Trillion (£68

[6] The current government is formed by one leading national party Bhartiya Janta Party (BJP). BJP is known for its support for ILR projects. The project was a major attraction in its electoral campaign in 1998-1999 (Pasi 2012). BJP led National Democratic Alliance which formed a central government in 1999 and pushed the project; however they lost elections in 2004 and 2009. In 2014, BJP won with a full majority and formed its own government.

billion)[7] in 2002-2003 which doubled to INR 11 Trillion (£134 billion) when adjusted to inflation, as estimated by MoWR of GOI (Jolly 2016).

The project includes two management levels: Inter-state and intra-state (NWDA 2017) (Figure 2.5).

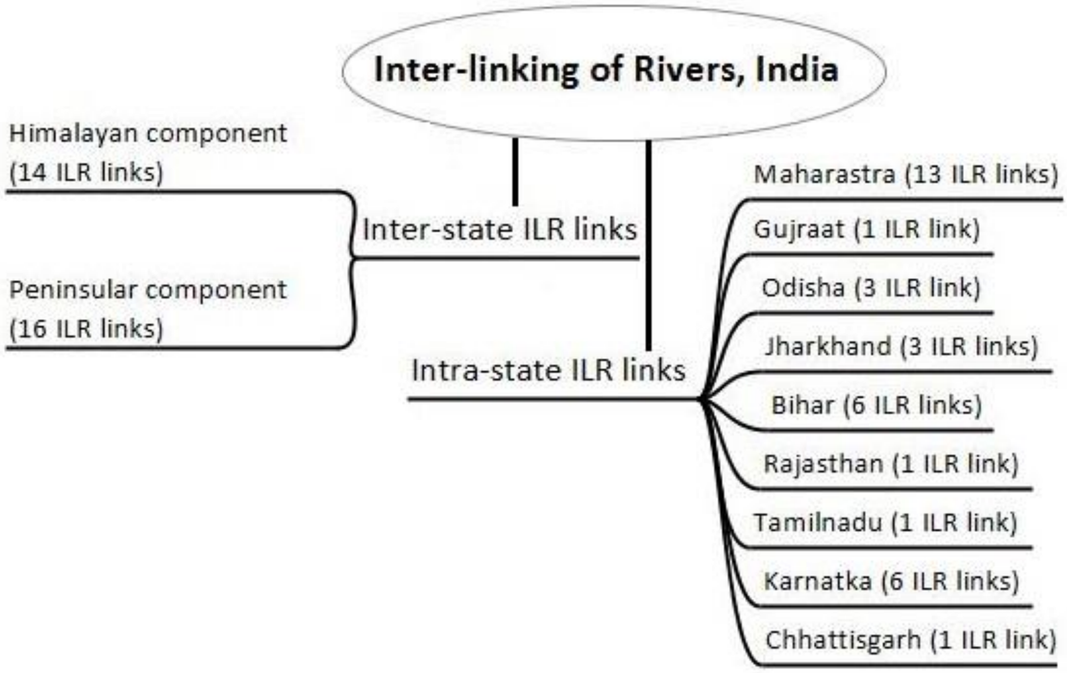


Figure 2.5: Inter-linking of Rivers (ILR) Project – levels and components

Inter-state level ILR links are proposed and managed by the central government of India. There are 30 ILR links, grouped in two major components: Himalayan (14 ILR links) and Peninsular (16 ILR links) (Figure 2.5). Feasibility studies[8] for two ILR links in the Himalayan component and 14 ILR links in the Peninsular component have been completed (MoWR-GOI 2016) and detailed progress reports on four links have been prepared (NWDA 2017). Completed feasibility reports on 14 ILR links and detailed progress reports on three ILR links from the Peninsular Component are available in the public domain via the NWDA website (NWDA 2017). For the Himalayan Component, no feasibility study is available on the website; however, a detailed progress report on one intra-state ILR link is available.

[7] Currency conversion used (dated 17.06.2017): 1 (INR) = £ 0.0121415.
[8] For inter-state links, first feasibility studies have been carried out which are being followed by a detailed progress report.

Intra-state level ILR links are proposed by state governments of India; however, they are being studied and managed by NWDA (NWDA 2017). A total of 46 ILR links have been proposed by several governments, of which 11 have been declared unfit by NWDA (NWDA 2015). Pre-feasibility[9,10] reports on 27 ILR links are complete and for the other eight ILR links, pre-feasibility reports are in progress (NWDA 2015). For intra-state ILR links, no feasibility studies are available in the public domain; however, a detailed progress report for one intra-state ILR link (in Bihar[11]) is complete (NWDA 2015) and is available on NWDA's website (NWDA 2017).

Pre-feasibility reports for the links of interest (NWDA 2009a; 2009b) were collected from the Department of Water Resource, Government of Jharkhand in August 2013. Detailed progress reports of these links are not yet prepared (NWDA 2016b). By the time data collection had been completed for this research, detailed progress reports were either not completed or not available in the public domain. Therefore, they have not been taken into account while writing the following section. Any report and information which subsequently becomes available will be addressed in the discussions while evaluating the results of this thesis.

2.3.1.3 Elements of NWDA studies: a critique

Smakhtin et al. (2007, 2008) underlined that all the reports by NWDA of GOI are 'succinct summaries' (2008, p. 87) of proposed ILR links and they all have similar chapters and levels of detail. The chapters of NWDA's reports generally include an introduction, physical features, inter-state aspects, survey and investigation, water resource and hydrology, design (engineering structures), reservoirs, water and irrigation planning, command area development, power, construction programme (manpower and plant planning), environmental and ecological aspects, cost estimates, and financial aspects (cost-benefit ratio). Chapters related to engineering

[9] For intra-state links, pre-feasibility reports have been prepared which are being followed by a detailed progress report.
[10] NWDA did not make it clear why it used separate terms for the same studies in these two levels. Detailed inspection of these reports shows that both feasibility and pre-feasibility reports provide the same information in the same structure. Hence, the present thesis takes both reports as being the same, and not as later preceding the former.
[11] The links name is 'Koshi-Mechi' which is different from the inter-state ILR link of the same name (NWDA 2015a).

and design aspects are fairly detailed. The chapter 'Water Resources and Hydrology' (in some reports termed only 'Hydrology') provides details on water balance[12] analysis carried out, to calculate the amount of surplus water available to transfer. It only covered WA and WD in the upstream of the donor catchment which is not in the line of IBWT criteria-sets discussed above.

To calculate surplus WA, observed annual discharge at 75% dependability[13] was mostly used. However, in some cases 50% dependability was also used (NWDA 2014). The NWDA cited no reason to select these thresholds; these bases are most commonly used in the Indian water resource planning and management, especially the threshold of 75% dependability. Further, the observed period for discharge varied with links, ranging from around 10 to 35 years which might be explained by the period of data availability. However, here it is worth noting that the India-WRIS (2016) by CWC, GOI has nation-wide long-term daily discharge data available at a range of spatial scales covering from the level of river basins to the level of the Hydrological Observation Centres (HOC)[14]. Further for the surplus WA calculation, the observed annual discharge was converted into natural discharge by adding all water abstractions (export) and subtracting all additional water (imports); however the reports provided very limited details of the data used in it (Smakhtin et al. 2007). On the other hand, for some of the ILR links, the surplus WA in the donor catchment area was delineated on the basis of water yield at the basin[15] scale despite the availability of discharge data at finer spatial resolution (i.e. at HOC level) and also with the same or longer data periods (e.g. for Sankh-Subarnarekha and South Koel-Subarnarekha ILR links). Additionally, the surplus WA in the donor catchment of ILR links was calculated at an annual level using the annual discharge

[12] In NWDA studies, the term 'water balance analysis' has been used for the calculation of surplus surface water after fulfilling water demands of irrigation, domestic and industrial sectors. It does not represent the wide-spread notion of 'water balance' based on inflow and outflow of the basin's water as explained in Sokolov & Chapman (1974). Keeping the aim of present research, this thesis takes 'water balance analysis' to be the same as given in NWDA's studies.

[13] 75 % dependability denotes the amount of flow which is available in the river for 75 years out of 100 years (Reddy 2005).

[14] As per India-WRIS (2012) and CWC (2013), there are 25 major river basins in India which includes 101 sub-basins covering 878 hydrological observation centres (HOC). The sub-basins are further divided into watersheds; and are covered by one or more HOC monitored by CWC, GOI.

[15] The hydrological units practiced in WRM of India are (bigger to smaller): Regions (5), Basins (25), Sub-basins (101) and watersheds (4566) (CWC & NRSC 2014).

data, despite the fact that the daily discharge data at the HOC level is available to the CWC of GOI (India-WRIS 2016)[16]. Then, this annual surplus WA was used to deduce the monthly surplus WA, using the ratio of monthly and annual rainfall data at any nearby rain-gauges (Smakhtin et al. 2007).

The WD for the donor area considered in water balance studies was projected for 2050 which included domestic[17], irrigation and industrial WD. The domestic WD was estimated for the urban and rural population; no detail was given about the data used. The feasibility studies assumed that the full urban and half of rural WD were met by surface WA and the other half of the rural WD was fulfilled by ground WA; however, they did not cite any reason for this assumption. The reports further assumed, without citing any reason, that complete livestock WD was fulfilled by ground WA and thus, was not included in the water-balance calculations despite being mentioned in the report. The irrigation WD was estimated from completed, on-going and proposed irrigation projects. For industrial WD, the studies assumed it to be equivalent to total domestic WD (covering full urban and rural population) by citing the unavailability of industrial WD data. This assumption could under-/over-estimate the industrial WD. Additionally, there is no reason to support this assumption as industrial WD could be reasonably estimated (as done in Chapter 5). Further, again without citing any proper reason, NWDA used different water-use rates in the feasibility reports of different ILR projects in order to calculate the WD mentioned above (NWDA 2004; NWDA 2009a; 2009b) despite the similarity in the regions and in populations. Further, to accommodate downstream requirement of the donor basin, feasibility studies considered only a share of maximum irrigational potential (based on the area of upstream catchment) projected for the downstream basin and no other WD of the downstream donor catchment was included. The reports provided no information on the WA and WD of recipient basin.

The remaining chapters in the NWDA reports provided generalised and limited information related to the project area, ecology and environment, cost and benefits

[16] India-WRIS (2016) by CWC, GOI provides daily discharge data of almost all HOC in the public domain except for those HOC whose data is classified (mostly in lower Ganga and Brahmaputra River basins).
[17] In NWDA reports, the word 'domestic' has been used instead of 'municipal'.

along with a vague schedule and planning for execution (Alagh et al. 2006) and only technical details, such as water balance assessment and engineering work, were fairly detailed (Smakhtin et al. 2007, 2008). The reports were repetitive, with the same information given under different levels (e.g. state, basin, up-stream, command area etc.) (*ibid*). They failed to provide evidence in support of analysis, outputs and claims (Krueger et al. 2007). Further, no information was given on how the links will map into the regional development plans (Chopra 2006) despite earlier claims from NWDA (Parashar 1999).

2.3.2 Debate around the ILR Project

The ILR project is the “most ambitious project ever proposed” to address water scarcity in India (Khosla 2006, p.11) and has been contentious since its outset (Amarasinghe 2012). Since its launch in the public domain, a passionate discussion has been ongoing between protagonists and antagonists of ILR (Pasi & Smardon 2012) which is evident from the literature. Proponents find it essential for India to secure food and water by 2050, as well as to deal with the concurrent flooding and droughts and call its benefits extraordinary (Thatte 2006, 2009; Prabhu 2008). Opponents call it an illusion and find it technically and financially unconvincing and raise several concerns (Iyer 2002; Bandyopadhyay & Perveen 2008; Mehta & Mehta 2013; Koshy & Bansal 2016). Following is a succinct summary of this passionate debate. Here it should be noted that, similar to the pattern seen while discussing the benefit and concerns of IBWT in general (section 2.2.2), the literature supporting the ILR projects are also fewer in number than those critiquing it.

2.3.2.1 The ILR: Projected benefits

The ILR projects, when complete, will move 173 km^3 of water per annum through 15000 km of new waterways (Jolly 2016). It will increase Indian irrigation potential from 140 million to 175 million hectares (by 25%) and will also generate 34,000 MW of hydro-electricity per year (MoWR-GOI 2016).

The proponents of ILR claimed that the benefit from ILR project will exceed its cost (Murthy 2003; Bery et al. 2008). Parashar (1999) emphasising that the projects could bring overall socio-economic development to India and projected that these projects would "enhance agro-based industry" and "improve health and living standards" (p. 77). Thatte (2006) emphasised that the projects could reduce poverty, generate employment and curb rural to urban migration. Additionally, the ILR planners claimed that the projects will be beneficial to Indian ecology (Mohan 2014). Some of the other benefits are "flood-control, navigation, water supply, fisheries, salinity and pollution control" (NWDA 2015, p. 4).

2.3.2.2 The ILR: Current and projected concerns

Similar to the IBWT concerns in general, concerns outlined for the ILR projects are also grouped in modified version of six categories by Khosla (2006) (Table 2.1).

i) Decision-related concerns

The planning of the ILR projects is largely based on the project area instead of the overall catchments involved (Chitale 1992). The projects are largely in the early stage of water resource planning, termed as "inception" by Loucks et al. (2005).

The ILR projects are most criticised for their fundamental process of IBWT decision-making (Iyer 2012) which followed the basic concept[18] of surplus and deficit basins (Bandyopadhyay & Perveen 2003). The main reasons for this criticism include: the conceptual framework (Amarasinghe 2012) for ignoring vital inputs such as environmental needs and groundwater (Bharati et al. 2008), uninformed assumptions (Alagh et al. 2006), incorrect data (Smakhtin et al. 2007) and spatial as well as temporal scale (Smakhtin et al. 2008) leading to over-estimation of WA and WD (Vaidyanathan 2003) at annual and seasonal levels (Smakhtin et al. 2007). As India experiences a monsoon climate (Rao 1979), ignoring seasonal variation of WA could jeopardise ILR projects (Smakhtin et al. 2007, 2008). The ILR planners have given inequitable value to different WD across various regions despite the similarity between them (Thakkar & Chaturvedi 2006). These inconsistencies in WA and WD resulted in under- or over- estimation of the water balance in the catchments of the

[18] Concept used to decide surplus and deficit basin is based on an 'unpublished paper' by A.D. Mohile (Bandyopadhyay & Perveen 2003, p.8).

ILR projects (Amarasinghe & Sharma 2008). Further, the ILR plans also overlooked the influence of climate change in the water-balance assessments which could affect the outcome of these links (Sahoo et al. 2009). Additionally, the ILR plans ignored the reliability assessment of the ILR links in meeting its potential goal (Jain et al. 2005). They also overlooked the sustainability of all catchments involved in the ILR projects (Gupta & van der Zaag 2008).

The basic concept used to define the ILR links is an outdated traditional style of planning water resources that ignores environmental need and follows a supply-side approach (Amarasinghe 2012) which had been identified as problematic for the sustainable water resource planning in developed countries (Micklin 1984; Loucks et al. 2005). Further, this concept ignores the widely acknowledged criteria-sets of IBWT (section 2.2.4) as observed in the existing ILR plans, despite awareness of it (Parashar 1999; Thatte 2009). Furthermore, although some of the ILR plans were released by NWDA after the instruction of SCI to promote transparency in the ILR planning process, the plans provide inadequate information on the data used (Smakhtin et al. 2007, 2008) and fail to use the latest available data, methods and tools from different fields (Chopra 2006) along with the multi-disciplinary scientific understanding (Verdhen 2016). Moreover, the ILR planners have shown reluctance in facilitating public awareness and participation (Vaidyanathan 2004; Krueger et al. 2007). Thus, they have undermined The Dublin Principles which require data to be democratised by encouraging transparency and public participation in the planning of any water resource project (Solanes & Gonzalez-Villarreal 2009; Madhav 2010). As a consequence, it can be said that they have limited any independent evaluation of the ILR decision made, which has affected the credibility of the ILR plans (Prabhu 2008) and instigated conflicts (Jain et al. 2008); ultimately the progress of the ILR projects has been delayed (Pasi 2012). Mr S Prabhu (2008), the chairman of task-force (2002-2004) appointed by GOI advised ILR planners to encourage transparency and dialogue in the ILR planning; however, little has been done in this direction and public participation remained restricted as before (Pasi 2012). Thus, the problems for ILR projects have continued to persist as reported by Verdhen (2016), Jolly (2016) and Koshy & Bansal (2016).

The ILR plans demonstrate the supply-side approach of ILR projects which is the most-preferred approach to address the water scarcity in India (D'Souza 2003). These studies are inclined to technical perspectives and largely ignore the environmental and socio-economic conditions (Chopra 2006); thus overlooks hybridity of IBWT decision process which are discussed in further sections. Further, the existing ILR plans ignore current practices in the project area such as regional change in cropping patterns in areas under Ken-Betwa ILR project (Alagh 2006; Amarasinghe 2009). Several other discrepancies and omissions of details have been outlined in ILR plans such as area submerged (Thakkar & Chaturvedi 2006) and details of dams proposed (Patekar & Parekh 2006).

ii) Environmental Concerns

ILR could have disastrous ecological and environmental impacts (Gourdji et al. 2005; Bandyopadhyay 2012) by disturbing the uniqueness of the ecosystems of Indian river basins (Islam 2006). Plans could endanger Indian River basins prioritised for the protection of aquatic biodiversity[19] (Lakra et al. 2011). These links would "change depth, flow and turbidity of water" in rivers (Daniels 2004, p. 1030). Flow reduction and storage of water results in siltation which promotes eutrophication and decreased oxygen concentrations in the water body forcing the existing ecological system to change (Gourdji et al. 2005). Further, the reduction in flow could cause delta-retreat (Smakhtin et al. 2007, 2008) and destroy wetlands (Daniels 2004; Lakra et al. 2011)[20]. If constructed, the ILR projects could affect the rich biodiversity of Indian rivers (Daniels 2004). Further, it could transfer polluted water and risk pristine river basins (Lakra et al. 2011). Moreover, the links could facilitate invasion of alien species (Daniels 2004). On the other hand, as Indian water projects are prone to siltation (McCully 2001), ILR projects could also suffer from similar impacts which would affect their life-expectancy (D'Souza 2003).

[19] Currently nine out of thirty river basins prioritised for the protection of aquatic biodiversity in the world are located in India. They are Cauvery, Ganges–Brahmaputra, Godavari, Indus, Krishna, Mahanadi, Narmada, Pennar and Tapi (Lakra et al. 2011, p. 469)

[20] In support of all statements made, Daniels (2004) and Lakra et al. (2011) cited several examples of ecological disturbances by previous water projects in India.

ILR plans included a section on environmental and ecological aspects; however these only provide limited and vague information (Islam 2006; Smakhtin et al. 2007, 2008). Krueger et al. (2007) and Smakhtin et al. (2008) found that the ILR plans were insensitive towards bio-diversity. Smakhtin et al. (2007, 2008) highlighted that in the existing ILR plans, wildlife was expected to combat changes in physical environments on its own, which signified the poor status of mitigation efforts taken in the feasibility reports (Thakkar & Chaturvedi 2006). NWDA promised to conduct an environmental impact assessment (EIA) in detail (Mohile 2006). Prabhu (2008) admitted these problems with the ILR projects and acknowledged the lack of scientific studies and therefore, supported an extensive EIA to be carried out (Thakkar 2010).

iii) Social Concerns

The ILR plans are biased towards the engineering and physical sciences and neglect the socio-economic patterns (Chopra 2006) which is reflected in its poor assessment of displacement, resettlement and rehabilitation (Patekar & Parekh 2006; Smakhtin et al. 2007, 2008). If constructed, these projects could have massive social costs due to the enormous displacements it would cause (Radhakrishna 2003). Although some ILR plans have included the number of people to be displaced by reservoirs, they did not include any information about the population displaced by other associated entities such as canals (Patekar & Parekh 2006). Thakkar (2007, p. 7) estimated a conservative figure[21] of 1.5 million people to be displaced by the ILR projects. Further, Misra et al. (2007) pointed out the weaknesses in the resettlement and rehabilitation policies by GOI which are likely to be used for the ILR projects.

On the other hand, these reports ignored settlements and valuable land with incommensurable cost which could be submerged, as seen in Ken-Betwa link[22] (Patekar & Parekh 2006). Also, the ILR planners of Ken-Betwa link have not made

[21] The figure includes population displaced by dams and canals (Details in Thakkar 2007).

[22] Under Ken-Betwa ILR project, several villages and 9% of preserved forest will be submerged. Also the submerged area is within close proximity of immensely valuable archaeological assets such as “Khajuraho Temple” which is under archaeological investigation (Patekar & Parekh 2006).

effective efforts to inform the affected people which could also be the case in other ILR plans (Krueger et al. 2007). Further, ILR projects could adversely affect health in their area as seen in previous water projects (Gourdji et al. 2005). Additionally these projects are likely to affect native (tribal) people disproportionately as seen in other water resource projects (Thakkar 2003; Patekar & Parekh 2006). Proponents of the ILR projects consider these social impacts as a small price to pay for overall development (Pasi & Smardon 2012) and expects people to sacrifice their personal interests in the name of national interest (Pasi 2012).

The ILR planners are aware of the issues (Prabhu 2004) and have assured that it will be taken care of (Parashar 1999; Thatte 2006). However, given the past experience of large-scale water resource projects in India (Singh 2002; McCully 2001), it appears to be extremely difficult if not impossible. Therefore, it is highly likely that the ILR project will further generate mass opposition and conflicts (Chellaney 2011).

iv) Economic concerns

Proponents of ILR claim that it will bring economic prosperity by various means (Parashar 1999); however, they accept that it comes at a significant cost (Murthy 2003). The excessive cost of the ILR project attracted sharp attention (Radhakrishna 2003; Gupta & van der Zaag 2008). Rath (2003) outlined that the official cost estimates of the ILR project did not take interest payments or inflation into account; when both are considered, the costs tend to rise exponentially. This statement was reflected in the latest cost of the ILR project announced by the MoWR, GOI as it doubled since 2002-03 (Jolly 2016). Further, the ILR plans gave cost details of engineering works involved in ILR (Chopra 2006); however, it failed to include the social and environmental costs associated with the projects (Amarasinghe 2012). On the other hand, the actual cost of transferring water was not included in the cost estimation such as lifting of water through pumping (Chopra 2006; Vombatkere 2008). Nevertheless, arrangement of such huge funding is a major challenge for the ILR planners (Sahoo et al. 2009; Mehta & Mehta 2013). The cost of transferred water and electricity generated would be significantly higher which is unlikely to be affordable to the users (Rath 2003). Additionally, the ILR plans gave no detail of cost recovery (Mohile 2006).

Further, the challenges of cost and benefit distribution have also been ignored by the ILR planners (Duflo & Pande 2005; Bandyopadhyay & Perveen 2008). Moreover, the ILR planners took the standard practices of cost-benefit analysis used in India (Chopra 2006); numerous examples of evidence of this method's failure have been cited by Singh (1997), McCully (2001) and Sharma et al. (2008). Moreover, the distribution of cost and benefit could be a significant challenge in the ILR project (Prabhu 2008) and its negligence could provide opportunities to be manipulated later by socially and politically influenced communities (Chopra 2006). Several such examples from previous water projects in India have been cited by Duflo & Pande (2005) and Sharma et al. (2008).

v) Legal and policy concerns

In India, water is managed by the state which frames related law and policy (Narain 2000) and central/national/federal government is largely responsible to guide states leading to integrated development of water systems and solve any inter-state water conflicts (Chellaney 2011). At the national level several departments handle different water-related issues (Centre for Science and Environment (CSE) 2004) and clear-line authority is absent (Chellaney 2011) which leads to a fragmented and disorganized approach to water governance (Chellaney 2011; CSE 2015). It has resulted in several water-related conflicts at national and international levels (Narain 2000). The SCI has intervened frequently to resolve many of them, however, given the complex and multi-disciplinary nature of water management these conflicts have lingered for years in one way or another (Chellaney 2011).

The ILR links could only come into existence when respective states come to mutual agreement (Iyer 2003b). Central government can play an important role in persuading states using some of its exclusive powers (Chellaney 2011); however, it had been reluctant to use these powers in the past (Iyer 2003b) which could be due to electoral reasons (Singh 2002) and/or corruption (Gichuki & McCornick 2008). Although MoWR has requested cooperation from states (NWDA 2016b), it is far-from being achieved (Iyer 2012) as conflicts are emerging among the states (e.g. Thakkar & Chaturvedi 2006; Jolly 2016). Moreover, water-related disputes are common among its various stakeholders; however, the legal mechanism in India infamously lacks the ability to resolve them (Vaidyanathan 2004) due to the inefficient water management institutions in the country (Narain 2000). Also, although water-sector law has been reformed using the guidelines from The Dublin Principles, its influence is limited on the Indian water management and therefore water resource projects in India still lack transparency and public participation (Madhav 2010) which fuels misinformation and conflicts (Prabhu 2008). Thus, it is likely that water-disputes could escalate due to the ILR projects (Iyer 2003a; Gupta & van der Zaag 2008; Ahmed 2012).

Further, although the new National Water Policy (2002) cautioned use of transferred water for achieving equity and social justice (MoWR 2012, p. 6) and encouraged WD management before considering long-distance water transfer (MoWR 2012), it all seems a distant dream due to the prevalent supply-side approach (Korse 2004), lack of coordination at different levels, scientific bias and ignorance of multi-disciplinary assistance and lack of direct accountability (Narain 2000). Furthermore, active monitoring by the SCI (section 2.3.1.1) without giving much thought to its impact, has provided an undue push to the project and undermined the executive domain (Iyer 2012) resulting in a rush to complete the project (Bandyopadhyay & Perveen 2004). For this reason, Iyer (2002, 2003, 2006, 2012) called ILR a product of judicial activism. Alley (2004) called it a double-edged sword while Chellaney (2011) praised it. This push could also contribute in immature handling of the processes of the ILR projects, omissions of important facts and negligence of law as noted by Chopra (2006), Patekar & Parekh (2006) and Prabhu (2008).

vi) Strategic Concerns

On the basis of projected benefits of the ILR projects (section 2.3.2.1), the ILR planners justified the projects and called them beneficial for the 'national interest' (NWDA 2016b). They followed the opposite route of decision-making while deciding the projects i.e. to pose the solutions first and then relate it to the different problems it can address (Bandyopadhyay & Perveen 2004). However, they were extensively criticized by the experts and communities for these strategic attempts (Alley 2004; Bandyopadhyay 2012).

The NWDA projected the ILR projects as a critical solution to meet the irrigation WD in order to meet the food requirements by 2050. However, this need for irrigation expansion has been questioned on several grounds. Amarasinghe et al. (2007, 2008) suggested that the projected WD to ensure food security by 2050 is exaggerated while Iyer (2012) stated that before bringing extra water through transfers, the reasons for lower irrigation efficiency must be addressed as the current average irrigation water efficiency is only 35% (Bandyopadhyay 2012). Moreover, it is not entirely clear whether the projects would cover new or old irrigation areas (Smakhtin et al. 2008). However given the low irrigation efficiency prevalent, the planning of any ILR link must be questioned if it is proposed to provide extra water to the already irrigated areas (Iyer et al. 2012).

The ILR planners cited flood-control and drought mitigation as other reasons to transfer the water (NWDA 2017). However by citing the example of the Ganga[23] River basin, Iyer (2012) indicated that significant flood-control would not be possible. Further, he doubted the effectivity of the ILR projects in mitigating drought at a large scale as most of the drought-affected areas are in uplands while NWDA has claimed ILR links to be largely run by gravity (Singh 2003) and with minimal water-lift (Thatte 2006). On the other hand, the ILR planners did not show any efforts in considering alternatives while deciding on the water transfer projects (Radhakrishna 2003; Amarasinghe 2009; Amarasinghe 2012; Iyer 2012). However, Iyer (2003a) cited many examples from other parts of India suggesting that WD management could significantly combat the projected water deficit.

[23] Iyer (2012) stated that River Ganga could reach a discharge-rate of 2 million cusec (~ 57000 m^3/sec) during flooding. MoWR, GOI is planning to transfer 1500 m^3/sec from it to River Cauvery (Rao 2003). Rao (2003) also pointed out that MoWR, GOI is aware that normal flood discharge rate of Ganga River is between 30000-60000 m^3/sec and it much larger than the water transfer rate proposed.

Further, the "powerful coalition" of "engineers, financiers and politicians" recognised by Gumbo & Van Der Zaag (2002, p.811) appears to be influential while deciding the ILR projects (Shukla & Asthana 2005; Gupta & van der Zaag 2008). Their strategy to call the ILR projects 'in the national interest' (NWDA 2016b) has worked successfully and driven national passion in support of the projects (Pasi 2012). However, this strategy has been decried by academics and expert communities from different disciplines, and concerned citizen groups (Alley 2004; Bandyopadhyay 2012). Their efforts in highlighting the associated risks and uncertainties by critics have paid off to some extent, but the ILR planners' strategy of limiting access to related information and lack of strategic coalition among opponents from different field has hampered the opposition (Pasi 2012). Nevertheless, due to the efforts by critics, ILR planners are struggling to justify the projects (Pasi & Smardon 2012).

2.3.3 The ILR Projects: uncertainties and advice

The GOI proposed a series of IBWT links as the ILR projects to address a range of water-related issues which mainly includes ensuring WD to achieve food security by 2050 and controlling the concurrent flooding and drought in the country (Thatte 2006, 2009). Although the project is exceptionally expensive, the proponents claimed that its benefits would exceed its cost (Bery et al. 2008) and will bring overall socio-economic development in India (Chellaney 2011). The major projected benefits its proponents claim include: 25% increase in the agricultural potential of India by 2050, generation of 34,000 MW of hydro-electricity per annum, flood-control, drought mitigation, and water supply to various users (NWDA 2017). However, critics of the ILR projects argued that the claims are vague and overstated (Smakhtin et al. 2008; Iyer 2012); thus the ILR projects are unlikely to succeed in meeting its projected claims (Iyer 2012). They called the projects ambitious and raised several concerns regarding the project (Khosla 2006) including: inconsistent decision-process (Iyer 2012), ecological and environmental impact (Lakra et al. 2011; Bandyopadhyay 2012) and social concerns (Patekar & Parekh 2006). They also highlighted several economic (Rath 2003; Mehta & Mehta 2013) as well as legal and policy issues (Iyer 2003b; Ahmed 2012). They criticised the ILR planners for: following the opposite route of decision-making (Bandyopadhyay & Perveen 2004) and supply-side approach (D'Souza 2003) and limiting the application of reformed water policies based on international guidelines (Madhav 2010) which acknowledges hybridity and promotes data democratisation in water resource planning and management (Solanes & Gonzalez-Villarreal 2009).

The growing concerns of ILR planning, given the history of previous Indian water projects (Singh 2002; McCully 2001), cautions that if the concerns related to ILR are not addressed in time, they can become a bottleneck for the ILR project; ILR planners would therefore struggle to justify these projects (Pasi & Smardon 2012). Therefore, for successful planning and management of the ILR project, it is essential to plan on the basis of sound science covering hybrid understandings of the catchments involved (Chopra 2006; Prabhu 2008) using all vital inputs (Bharati et al. 2008), informed assumptions (Alagh et al. 2006), suitable datasets and spatial as well as temporal scales (Smakhtin et al. 2007; 2008), and the latest multi-disciplinary tools and methods (Chopra 2006; Jain et al. 2008). The planners should use an integrated approach to ensure the sustainability of the donor and recipient catchments (Gupta & van der Zaag 2008). They must ensure the reliability of the catchments and the ILR links (Jain et al. 2005). Moreover, they should promote data democratisation to ensure transparency and public participation in the planning process which would ultimately benefit the ILR projects (Prabhu 2008; Pasi 2012). Thereby, on the basis of these suggestions, a detail study for each of the ILR links is warranted under a holistic approach (Bandyopadhyay 2012).

Further, ILR planners must carry out the EIA in order to evaluate the associated environmental concerns in all catchments involved before finalising the ILR link (Lakra et al. 2011). Also, a comprehensive social impact study is urgently required in advance for each ILR link (Misra et al. 2007) which will assist in delineating suitable policies for the resettlement and rehabilitation of the population due to be affected by the project (Patekar & Parekh 2006). Also, an extensive economic feasibility assessment is needed in advance (Bandyopadhyay 2012) which must also include environmental and social costs (Amarasinghe 2012) and the economic viability of these projects must be assessed in detail (Chakravartty 2011). Moreover, the success of ILR projects would also require an accountable, well-coordinated inter-disciplinary and integrated organisational infrastructure (Narain 2000; Patekar & Parekh 2006).

Addressing these concerns in advance is essential for the successful implementation of the ILR projects (Chellaney 2011). Following this advice will: assist in resolving the conflicts, facilitate smooth planning and management of the project and support the justification of these projects (Verdhen 2016). To counter the criticism for the bias due to political influence or coalitions between politicians, engineers and financiers (Gumbo & van der Zaag 2002), studies by non-governmental platform would be beneficial for the ILR projects (Gupta & van der Zaag 2008).

2.4 The ILR project and the global IBWT: major features, gaps and recommendations

The review of the benefits and concerns regarding IBWT projects at global and Indian level showed significant similarity (section 2.2.2 and 2.3.2). Their main features, gaps and recommendations are as follows:

1. IBWT projects are multi-purpose projects which are primarily built for municipal, irrigation, industrial need and hydro-power generation. They have been praised for their benefits but they have also been criticised extensively.
2. The construction of IBWT projects has reduced in developed countries since environmental awareness rose in the 1970s; however, it is still a preferred option in developing countries.
3. The planning and management of IBWT is complicated involving other complex components WA and WD of both donor and recipient catchments and involves a range of stakeholders with contradictory desire; thus it is a wicked problem.
4. The IBWT criteria-sets have been proposed and evolved with time. They have made efforts to include the latest principles of WRM. However, among all of

them, the criteria-set proposed by Cox (1999) has been the most widely used and applauded by scholars.

5. The following gaps have been identified in the planning of IBWT projects and can stall and jeopardise these projects:
   5.1 The decision-making process of IBWT suffers from:
      5.1.1 use of wrong or uninformed assumptions, incorrect inputs, wrong spatial and temporal scales, ignoring annual and seasonal variability, inequitable value different stakeholders and regions,
      5.1.2 outdated conceptual framework,
      5.1.3 use of traditional methods and tools,
      5.1.4 ignoring the influence of climate change,
      5.1.5 undermining reliability i.e. ignoring risks and vulnerability,
      5.1.6 the challenges in data management: collection, processing and compilation on coherent basis,
      5.1.7 use of technical-side studies in deciding the project which undermine the hybridity of IBWT decision-process,
      5.1.8 lack of transparency and public participation limiting the evaluation of the decision made,
      5.1.9 outdated approach: supply-side.
   5.2 The ecological and environmental issues of IBWT, if not addressed, could cause problems such as:
      5.2.1 violating the limit of minimum environmental flow in the donor river,
      5.2.2 affecting the downstream morphology, dry up wetlands and trigger delta retreat in the donor basin leading to sea-water incursion,
      5.2.3 promoting wasteful use, transport pollution, could cause water-logging and salinization in the recipient basin,
      5.2.4 potentially affecting erosional and depositional powers of rivers thus their sediment transportation leading to problems such as undermining the infrastructure, low water-quality and siltation of spawning grounds,

5.2.5 adversely affecting bio-diversity of donor as well as recipient rivers,

5.2.6 jeopardising their ecological services,

5.2.7 causing enormous cost in restoring environmental health.

5.3 The planning and management of IBWT could face substantial societal challenges such as:

5.3.1 managing resettlement and rehabilitation of people,

5.3.2 dealing with vulnerable populations,

5.3.3 assessment of social costs and compensations,

5.3.4 assessment of adverse impact on health.

5.4 The IBWT planners could face significant economic challenges such as:

5.4.1 cost estimation including commensurable and incommensurable costs,

5.4.2 arrangement of funds,

5.4.3 pricing of water,

5.4.4 cost-recovery,

5.4.5 costs-benefits distribution.

5.5 The planning and management of IBWT projects include several legal and policy challenges such as:

5.5.1 complexities due to multiple jurisdictions,

5.5.2 ignoring prevailing laws and policies,

5.5.3 formulation of related law or policy,

5.5.4 neglecting transboundary issues,

5.5.5 institutional inefficiencies and their lack of cooperation,

5.5.6 misuse of legal systems,

5.5.7 lack of appropriate mechanisms hindering the implementation of relevant legal acts and polices.

5.6 The IBWT planners face frequent criticisms for their strategies such as:

5.6.1 poor justifications such as national interest,

5.6.2 monopolistic and secretive attitude,

5.6.3 planning approach,

5.6.4 ignoring alternatives,

5.6.5 opposite route of decision-making: in the case of the ILR projects.

6. Thus IBWT planning and management is challenging, and prone to inconsistencies, if not planned carefully. If these concerns are not addressed in advance, they could lead to erroneous decisions resulting in conflicts and disrupting these highly ambitious and expensive projects.
7. Being hybrid and wicked in nature, the IBWT projects require careful planning. Based on the review of studies, policies and practises at both the global and Indian scale, the following recommendations have been made for the planning of any successful IBWT project:

7.1 The decision-making process of IBWT links should:

7.1.1 be based on an integrated and holistic approach,

7.1.2 include WA and WD of both donor as well as recipient catchments,

7.1.3 have a sound scientific base,

7.1.4 cover multi-disciplinary understanding of the area involved,

7.1.5 make informed assumptions, include all vital inputs, use suitable and reliable data with refined spatial and temporal resolution,

7.1.6 use latest available methods, tools and expertise from different discipline involved,

7.1.7 assess annual as well as seasonal variability,

7.1.8 consider the influence of climate changes,

7.1.9 ensure reliability of the catchments and the ILR links,

7.1.10 ensure the sustainable development of the catchments,

7.1.11 practice data democratisation encouraging transparency, public participation and awareness.

7.2 The IBWT project must address its ecological and environmental concerns; therefore a thorough EIA is essential and must be carried out before finalising the decision for the IBWT link.

7.3 A detail social impact study must be carried out before finalising IBWT links so that informed decisions can be taken by the IBWT planners. Mitigation plans including the plans to make justified compensation must be made in advance. Also it must be discussed and agreed before the construction of the project starts.

7.4 An extensive economic evaluation of IBWT project, including: social and environmental costs, arrangement of the funds, cost-recovery, equitable cost and benefit distribution and justifiable pricing is needed before making the final decision for IBWT links. The plan should also include risks of cost overrun and the economic viability of the project.

7.5 The IBWT planners should ensure that all relevant polices and guidelines are met before finalising the project. Also efforts should be made for a transparent, accountable, well-coordinated, inter-disciplinary and integrated institutional infrastructure. It will assist in making informed policy related to the project as well as in raising awareness regarding the project.

7.6 The IBWT planners should ensure that alternative water within the basin sources, such as water demand management, has been explored. They must have sound justification for the transfer of water.

8. Following these recommendations would facilitate the smooth planning and management of the IBWT project, support the justification of the project and allow the sustainable functioning of IBWT link along with the sustainable development of all catchments involved.
9. Therefore, using the above recommendations, scholars have emphasised a detail study of each IBWT link covering one or more concerns.

2.5 The research rationale and style

The ILR critics largely focused in framing the concerns in a generalised way covering the wider range of issues which created an informed audience for the ILR project (Pasi 2012). It was also evident while doing this literature review; and was noted that only a few pieces of research addressed any specific concern and/or link individually. Also, there is massive gap in studies by researchers, other than ILR planners, examining ILR links, and that too, on an individual basis. Thereby, a significant gap was noted for such study. This gap is being addressed in the present thesis. Further, it was also observed that there is a large range of concerns for the ILR project, covering the six themes (section 2.3.2.2), which need to be addressed. Most of them must be addressed before finalising the ILR project, among which decision-related concerns are most fundamental as they provide the foundation of the project, which, if not explored correctly, will potentially leave the seeds of conflicts at the project's core. Therefore, this thesis is addressing the decision-related concerns of the ILR projects and thus examining the decision-process of the two ILR links under study.

The core of decision-related concerns (section i)) largely covered matters of:

- data democratisation (transparency and public participation),
- approach (sound scientific, multi-disciplinary, sustainable, integrated and holistic),
- methods (best-practice and hybrid)
- tools (state-of-the-art and user-friendly, straightforward but robust),
- scales (appropriate spatial and temporal)
- data (suitable, latest and reliable)

In order to make this research transparent, accessible and, in accomplishing the thesis's aspiration, to strengthen the ILR decision-making process in India, these matters influenced the research style adopted in this thesis and inspired the following:

- using sound scientific and best-practice methods from different disciplines involved in order to make the research robust,
- using publicly available data (most suitable, latest and reliable) with appropriate scales (spatial and temporal) as well as tools (robust and state-of-the-art) as it encourages transparency and public participation and allow independent evaluation by anyone interested; thus the reliability of research undertaken is enhanced,
- acquiring a holistic and multi-disciplinary understanding of the catchments covering the hybridity of WRM,

- developing an integrated assessment of the potential surplus/deficit of water based on best-practice in the IBWT field,
- assessing the risks and vulnerabilities involved in order to ensure the reliability and thus sustainability of the ILR project and its catchments,
- critiquing current practice of the ILR decision-making process and providing recommendations to strengthen it.

2.6 Objectives of thesis

Based on the above discussion, the thesis defined the following objectives to achieve its aim:

Objective 1: Use of publicly available datasets and tools in order to evaluate their roles in understanding the IBWT decision-making process.

This objective will explore the role of publicly available datasets and tools in the IBWT decision-making process in order to promote data democratisation within it. Thus, it will address the current limitation on independent review of the ILR decisions made which has been caused as a result of the undermining of The Dublin Principles by the ILR planners.

Objective 2: Characterisation of the catchments involved in the two ILR projects under study (Landscape, hydrological and socio-economic).

This objective will provide the holistic and multi-disciplinary understanding of the catchments involved in the two ILR projects under study, covering current and relevant landscape features, hydrological behaviour and socio-economic patterns in the catchments. The understanding acquired will assist in the development of integrated assessment for IBWT links (Objective 3) and will provide a base to explain the outcomes of the research. This objective will be covered in Chapter 4.

Objective 3: Development of an integrated assessment of water availability and demand in the donor and recipient catchments of IBWT projects enabling an evaluation of existing IBWT plans for the links.

This objective will develop an integrated appraisal based on the widely acknowledged IBWT criteria-sets by Cox (1999) in order to examine the potential surplus/deficit of water in the donor and recipient catchments of the two ILR links. The outcome of this objective will be used to critique the existing ILR plans. Also, the developed assessment will form the basis of simulation undertaken in Objective 4. This objective will be covered in Chapter 5.

Objective 4: Performance assessment of the ILR links and their catchments through their simulation under a range of scenarios using the methodology developed.

Under this objective, the two ILR links and their catchments will be simulated and their performances will be assessed in order to analyse: first, the influence of water transfer on the catchments and second, functioning of the two ILR links. The outcomes of this objective will assist in examining the risk and vulnerability of the ILR links and their donor and recipient catchments. This objective will be covered in Chapter 6.

Objective 5: Recommendations for the IBWT decision-making process in India and in general.

Under this objective, first the decision-making process of existing ILR plans will be critiqued using the outcomes from previous objectives. Based on the understanding acquired from the critique, as well as from the outcomes of this research, recommendations will be made to strengthen the IBWT decision-making process in India and in general. This objective will be covered in Chapter 7.

2.7 Summary

This chapter has explored the current status of IBWT and ILR projects using a comprehensive sub-set of literature. The detailed review of lineage, benefits, and concerns of IBWT at the global scale provided the broad understanding of IBWT and helped in identifying the best practices and advice in the IBWT field. It also assisted in contextualising this thesis. The chapter then investigated the ILR projects covering their overview and associated debate about their benefits and concerns. The review led to the identification of the uncertainties accompanying the ILR projects. This review of the ILR projects positions this thesis in the wider picture of IBWT; the gaps outlined in these IBWT projects in India resonate with those at the global scale. The chapter then discusses rationale and style of this thesis which defines the objectives in order to achieve the aim of this research.

Chapter 3 Details of methodological approach, data, model and the study area

3.1 Introduction

This chapter provides details of the methods and materials used in this research. It includes the research approach taken (section 3.2), data collection and processing (section 3.3) and a description of the study area (section 3.4) with specifics of the two ILR projects under study (section 3.4.1) and the definition of the catchments involved in these two projects (section 3.4.2).

3.2 Methodological approach

The literature review has delineated the advice and best practices in Inter-basin water transfer (IBWT) decision-making processes so far which has assisted in the adoption of the research style and delineated the objectives of this thesis in order to fulfil its aim (Chapter 2). Based on these discussions, this thesis has five major elements:

1. Use of publicly available data and tools,
2. Characterisation of the catchments,
3. Integrated assessment of the water availability and demand in the catchments,
4. Performance assessment of ILR links and catchments, and
5. Critiquing the existing ILR plans and providing recommendations.

These five elements each address one objective of this thesis (Figure 3.1). Element 1 is embraced throughout the thesis. Elements 2-5 are covered in Chapter4-7 respectively. Chapter4-7 presents the methods for each element of the research and resulting outputs are then brought together in Chapter 8.

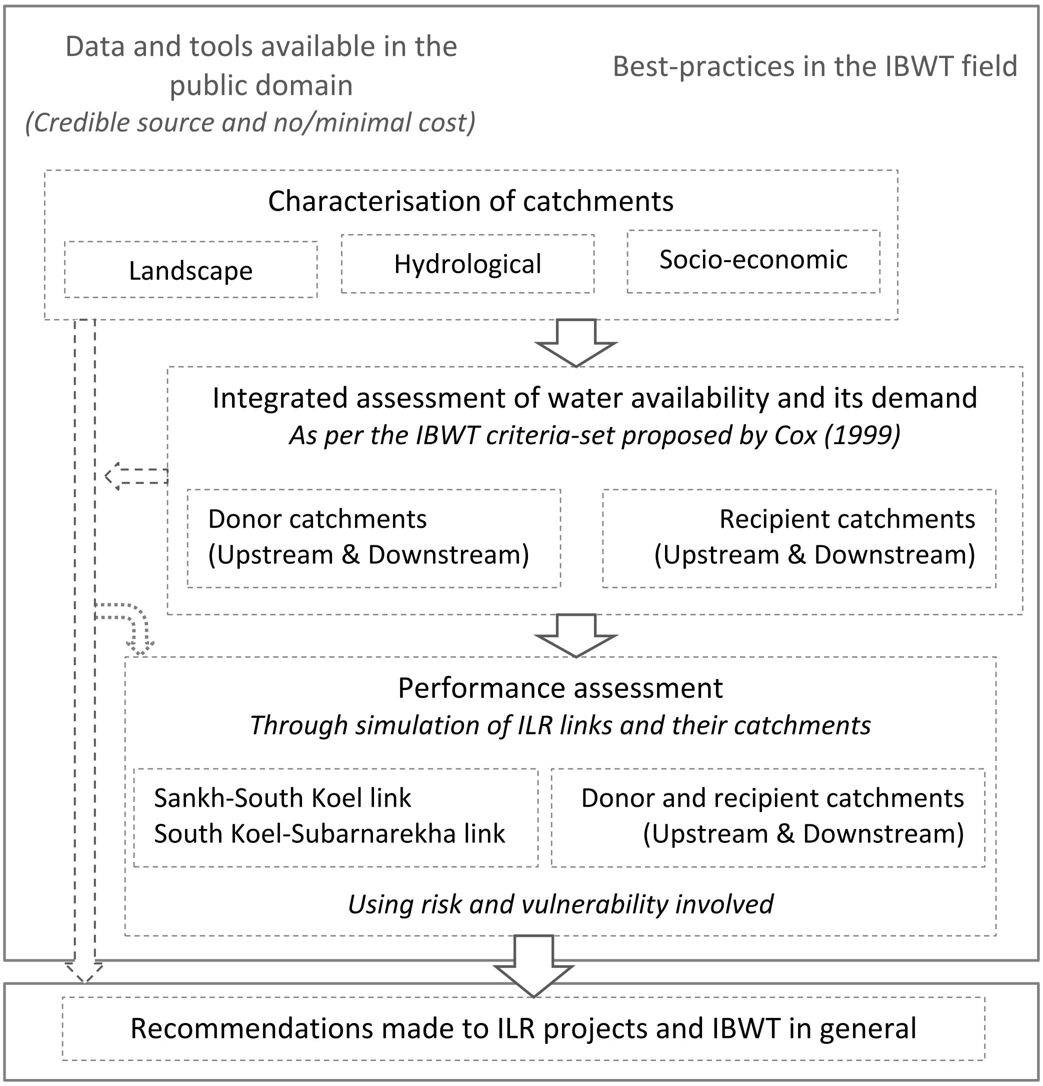


Figure 3.1: Flow diagram of the methodological approach adopted in this thesis.

Following sections briefly describes these five methodological elements.

3.2.1 Use of publicly available data and tools

Following the guidelines of The Dublin Principles i.e. The Dublin Statement on water and sustainable development (WMO 2017), the planning and water management of any water resource project should follow data democratisation in its decision-making process (Solanes & Gonzalez-Villarreal 2009). However, it was undermined by the planners of the Inter-linking of Rivers (ILR) project that limited independent evaluation of their decisions (section 2.3.2.2). This gap is addressed by the first objective of this thesis which explores the role of publicly available data in the ILR decision-making process enabling its independent evaluation by any interested parties. All relevant data are collected from credible sources in the public domain, largely from government sources and with no or minimal costs. The data collected is refined and processed to prepare catchment-based inputs. Wherever possible, the data are verified from various related reports and/or outputs by other methods. Their details are given in section 3.3. Similar to the use of publicly available datasets, the present thesis uses state-of-the-art tools available in the public domain. In order to maintain the robustness of this research but with minimum cost-implications, proven tools are selected and minimal costs has incurred.

3.2.2 Characterisation of the catchments

This methodological component covers the second objective of the thesis. It provides a multi-disciplinary understanding of the hybrid nature of the catchments involved in the two ILR projects under the holistic approach and is reported in Chapter 4. The research undertaken characterises landscape (Colby 2003; Biggs et al. 2007), analyses hydrological behaviour (Ceballos & Schnabel 1998; Bracken et al. 2008; Morán-Tejeda et al. 2012; Burt & Weerasinghe 2014) and explores socio-economic conditions (Loucks et al. 2005; GWP 2009) in all catchments involved. The findings from these characterisations depicts the status and trends of different bio-physical and socio-economic components that could affect water availability (WA) and water demand (WD) in the catchments (GWP 2009). The outcomes from this methodological unit also contribute to:

- the assessments being carried out in Chapter 5 (Objective 3) and Chapter 6 (Objective 4) by assisting in identification of vital inputs, informing assumptions and supporting the explanations of their outputs.
- Critiquing the existing ILR plans (pre-feasibility reports) of the two ILR links and assisting in the development of the recommendations for IBWT in Chapter 7 (Objective 5).

3.2.3 Integrated assessment of the water availability and its demand in the catchments

This methodological component covers the third objective of the thesis and is reported in Chapter 5. It develops an integrated assessment of WA and WD in the donor and recipient catchments of the two ILR links. The integrated assessment is based on the IBWT criteria-set proposed by Cox (1999) (Chapter 2, section 2.2.4) and modifies the methodology of the water-balance assessment used in the existing ILR plans of the two links by their planners (NWDA 2009a; 2009b). The understanding developed from the previous methodological unit is used at this research stage in identifying the vital inputs as well as in making informed assumptions for the integrated appraisal of WA and WD (Alagh et al. 2006; Bharati et al. 2008). The findings derived from this methodological unit provides the WA and WD in both donor and recipient catchments on both an annual and monthly basis (Smakhtin et al. 2007; Smakhtin et al. 2008). It provides an estimate of water surplus/deficit in donor and recipient catchments at 75% dependability (Cox 1999; NWDA 2009a; 2009b).

Further, the methodological framework developed in this stage of research forms the basis of the integrated simulation of the two ILR links and their catchments in the next stage of this research (Chapter 6). Additionally, the modified methodological framework also contributes to recreate the analyses performed in the two ILR plans, which was only limited to the donor basins and largely confined to upstream (section 2.3.1.3; section 3.4.1). The outcomes from the recreated analyses are used to critique the outcomes of the two existing ILR plans (NWDA 2009a; NWDA 2009b) and is reported in Chapter 7.

3.2.4 Performance assessment of ILR links and its catchments

This methodological component covers the fourth objective of the thesis and is reported in Chapter 6. Under this component, the two ILR links and their catchments are simulated to examine their performances on an annual and monthly basis (Loucks et al. 2005) through risk and vulnerability (Jain et al. 2005;

Gohari et al. 2013), under a range of current and projected scenarios for 2050 covering management policies including: without and with ILR link conditions, priorities to catchments or ILR links and two types of water source to meet rural and livestock WD (NWDA 2009a 2009b). The research at this stage uses:

- the integrated methodological framework developed in the third objective (Chapter 5) to simulate the ILR links and their catchments.
- the understanding developed in the second objective (Chapter 4) to make informed assumptions for the simulation, and also to interpret the modelling outcomes.

The annual and monthly outputs of the simulation were used to examine the performance of:

- the catchments through their risks in meeting their respective WD and environmental flow requirement.
- the individual ILR links: by their risk in meeting their proposed water transfers and by their vulnerability in meeting the proposed water transfers.

The research at this stage also explores the influences of climate change on projected water-balance in each catchment (Menzel & Burger 2002; Sahoo et al. 2009). It also examines the influence of the assumption made by NWDA (2009a 2009b) related to the water type used 'to fulfil 50% of rural WD' on the water-balance of each catchment .

The findings from this research stage assists in exploring if the donor and recipient catchments face any annual or monthly risk during current and future time-periods:

- in meeting their WD under business-as-usual scenarios based on water management policies (i.e. catchment conditions without ILR links), and
- in meeting their WD under water transfer scenarios based on water management policies (i.e. catchment conditions with ILR links).

The findings also explore if the two ILR links face any annual or monthly risk in meeting their proposed water transfer during the current and future time periods.

They also indicate the annual or monthly vulnerability of the two links during the current and future time periods. Thus, the findings explore the sustainability of the catchments and/or ILR links. They also contribute to critiquing the existing ILR plans in Chapter 7.

3.2.5 Critiquing existing ILR plans and providing recommendations

This methodological component covers the fifth objective of this thesis and is reported in Chapter 7. It uses the findings from the previous methodological elements of this research and critiques the existing ILR plans of both ILR links by (NWDA 2009a; 2009b) for its data, scales, tools, methods, approach and data democratisation (Loucks et al. 2005). It also discusses the role of publicly available data and tools in analysing the ILR decision-making process. On the basis of research experience, it also argues in support of the role of science-supported policy in dealing with the hybridity and wickedness of the IBWT projects. These discussions outline the recommendations drawn from this thesis for the ILR projects as well as for the IBWT in general.

Thus through this methodological approach, this thesis examines the two ILR links under study by exploring the theories around them. The research and its approach encourage transparency and indirect public participation by using publicly available datasets and model which are described in the following sections.

3.3 Datasets and tools

While collecting the datasets careful attention was paid to: source of data, consistency, spatial and temporal scale, and cost. Most of the data were collected from primarily responsible government departments. Only a few datasets, for which government data could not be traced, are taken from internationally reputable organisations (e.g. United Nations). Further, although the existing plans covered the project area within the Jharkhand state, the study area delineated in this research (section 3.4.2) also covered some parts of another three states

(Odisha, Chhattisgarh and West Bengal) (Figure 3.2). Therefore, to maintain the consistency of data among all states, data were collected from several departments of the Central Government of India. In some cases, inputs processed from these datasets were verified by respective data collected from the state governments or other departments.

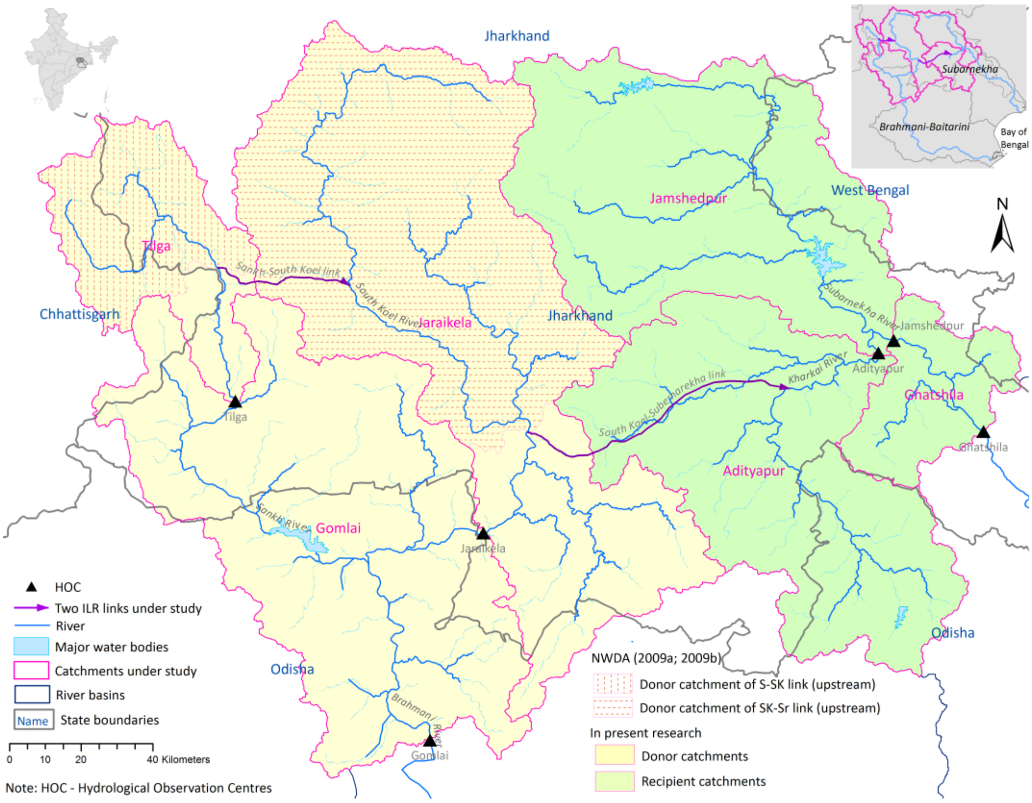


Figure 3.2: The states and the catchments of the two ILR links under study as per: the existing ILR plans (NWDA 2009a, 2009b) and the present study.

Furthermore, for some inputs district-based data were used to obtain catchment-based data due to: unavailability of catchment-based data, unavailability of data at a finer scale than district scale, time-limit of this research, the large scale of the study area and complexity of the IBWT projects. Moreover, to minimise the cost implications, data with no or minimal costs were used.

Following are the datasets along with their sources which have been used in this thesis:

	Data		Source
1.	Digital Elevation Model (DEM) of 3 arc-second (~90 m resolution) under HydroSHEDS project using datasets from Shuttle Radar Topography Mission (SRTM)	-	United States Geological Survey (USGS 2007)
2.	Land use and land cover (LULC) dataset (2005-06)	-	Watershed[1] reports (Figure 3.3) – by WRIS , GOI (India-WRIS 2016) (downloaded in 2013).

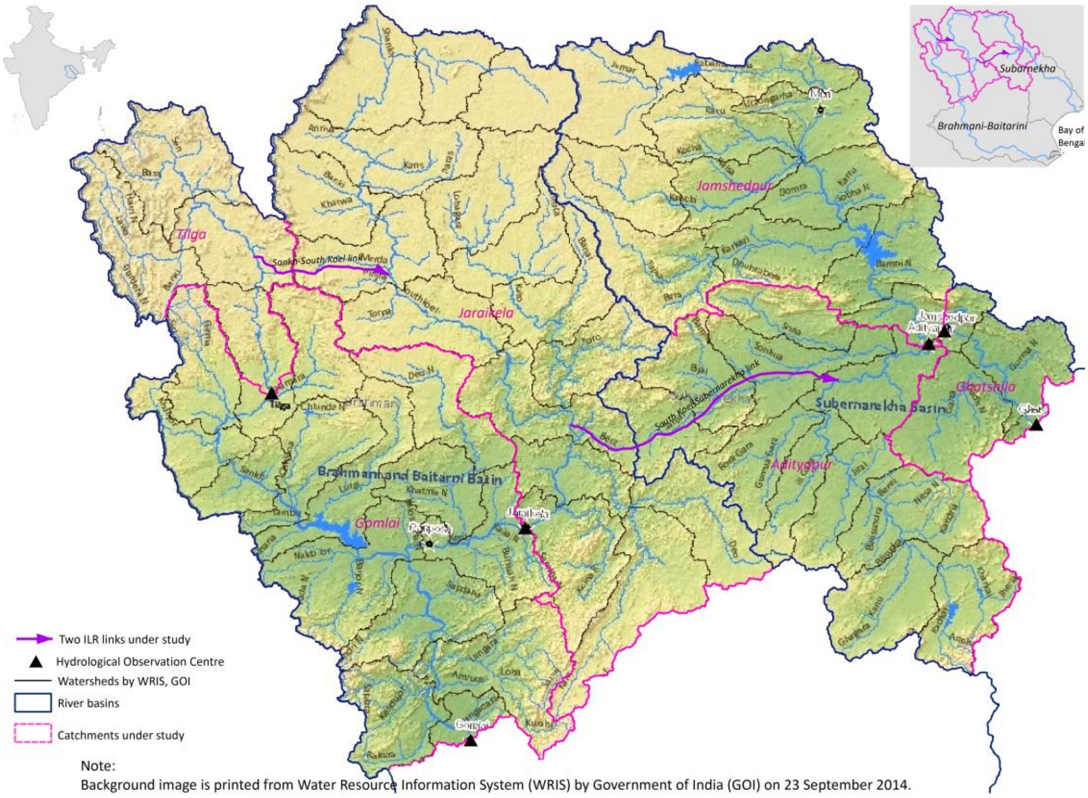


Figure 3.3: The six catchments under study overlaid on image[2] printed from WRIS, GOI (India-WRIS 2016) showing watersheds by CWC & NRSC (2014).

The LULC data are prepared at a scale of 1:50000 by the National Remote Sensing

[1] Watersheds are the smallest hydrological unit used by India-WRIS (2016). The other hydrological units are hydrological region, followed by basins and then sub-basins. Sub-basins are divided into watersheds (CWC & NRSC 2014, p. 10-12).

[2] The printed image also shows elevation ranging from yellowish (high altitude) to greenish (low altitude) shades.

Centre (NRSC) using Reseourcesat-1 LISS III satellite data for the period 2005-06 (NRSC 2006; India-WRIS 2016). For each watershed defined by CWC & NRSC (2014), a LULC report has been downloaded from India-WRIS (2016). Each of the six catchments under study comprise several of these watersheds by CWC & NRSC (2014) (Figure 3.3). The LULC data from these reports are summed up together to get LULC of all catchments.

3.	Geology and geomorphology (compiled from different reports by the Government of India (GOI)	-	Pre-feasibility reports by NWDA (2009a; 2009b), District ground-water brochures by CGWB (2015) and watershed reports (India-WRIS 2016)
4.	Gridded daily rainfall data with cell-size 0.5 degree (1971 – 2005)	-	Rajeevan and Bhate (2008) from Indian Meteorological department (IMD)

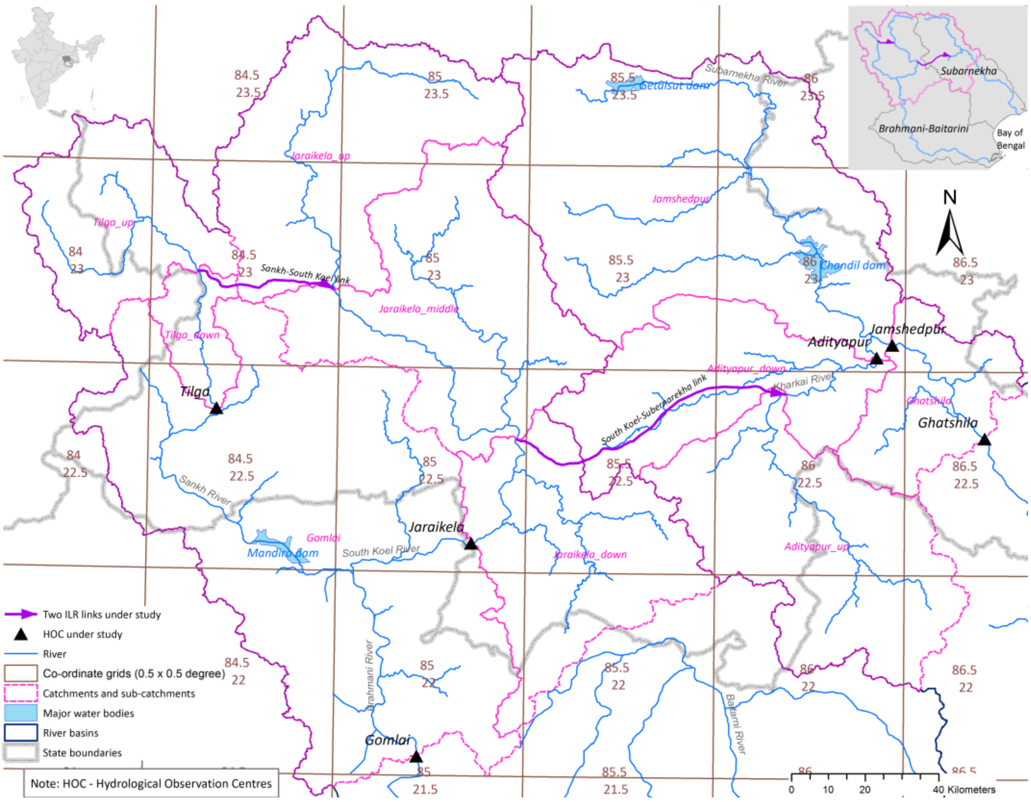


Figure 3.4: Catchments and sub-catchments in the study area along with the six hydrological observation centres (HOC) under 0.5x0.5 degree grids.

This rainfall dataset is used to calculate rainfall for each catchment using the area-weighted method. The area of each grid cell within each catchment is used to calculate the area-weighting for the rainfall of that particular grid cell (Figure 3.4). Then the weighted average rainfall of each grid is summed to get the total rainfall for the catchment.

5.	District-based data of Mean, Maximum & Minimum temperature (1971-2000) (noted from the source)	-	Water Resource Information System (WRIS), by GOI (India-WRIS 2016)

The mean temperature for each catchment is calculated using the area-weighted method as done for rainfall. The highest maximum temperature value and lowest minimum temperature value of all district-areas contained within each catchment are taken as the maximum and minimum temperatures respectively.

6.	Potential Evapo-Transpiration (PET) – mean annual and monthly data with 30 arc seconds (~ 1km at equator) resolution		Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2007; Zomer et al. 2008)
7.	Surface water (Major reservoirs)	-	River atlas of India (India-WRIS 2012).

Surface water data are only included for major reservoirs. The river and tributaries were delineated from the DEM.

8.	District-based ground water data	-	Central Ground Water Board (CGWB 2014)

The annual ground water availability and draft based on stage (%) for each catchment is calculated from district-based data of the same using the area-percentage method.

9.	Daily discharge data for six HOCs (Tilga, Jaraikela, Gomlai, Adityapur, Jamshedpur and Ghatshila) within the study area (Figure 3.4).	-	Water Resource Information System (WRIS), by GOI (India-WRIS 2016) - downloaded in 2013.

For each catchment, the flow is available for a period of 30 years or more.

10.	District-based population data of: Urban, rural with total number of population (1901-2011)	-	Census of India (Census-GOI 2011)

The total, urban and rural population datasets for each catchment are calculated from their respective datasets using area-percentage method. The total population of each catchment derived from this method is verified by the sum of their derived urban and rural populations.

11.	District-based occupational structure of population engaged in economic activity of (2011) (cultivators, agricultural labours, household industry and others)	-	Census of India (Census-GOI 2011)

The population engaged in each occupation for each catchment is calculated from their respective datasets using the area-percentage method.

12.	District-level data for livestock population	-	Technical note on the 19th Livestock census by Ministry of Agriculture (MOA) of GOI (2012).
13.	Irrigation-related data (irrigation projects and their command area)	-	Prefeasibility reports of Sankh-South Koel ILR link (NWDA 2009a) and South Koel – Subarnarekha ILR link (NWDA 2009b); Report by Regional Remote Sensing Service Centre (RRSSC), GOI (Sharma et al. 2007)
14.	Industrial water-related data	-	Water Resource Department, Government of Jharkhand (WR-GOJ) (2012) and Ministry of Micro Small & Medium

			Enterprises (MSME), GOI (2016).

Industrial water consumption data are loosely maintained by several departments of GOI and do not match with each other (Aggarwal & Kumar 2003; CSE 2004). While collecting datasets for this research, it has been observed that these datasets are not freely available in the public domain. However, they are available in government departments as evidenced in the case of Jharkhand (WR-GOJ 2012) contrary to the claims by NWDA (2009a, 2009b). Due to the unavailability of such datasets in the public domain, industrial water demand for catchments is derived as follows:

1. By subtracting the catchment-wise domestic water demand for Jharkhand state (calculated for 2011) from the catchment-wise domestic and industrial water demand data for year 2011-2012 taken from WR-GOJ (2012).
2. By multiplying the national average industrial water-use rate (derived using LULC and water withdrawal data for India from India-WRIS (2015) and the Food and Agriculture Organization of the United Nations (FAO 2015)) with:
   - 2.1. Industrial area derived from land use and land cover of catchments from India-WRIS (2016).
   - 2.2. Total industrial area derived from district-level reports by Ministry of Micro, Small & Medium Enterprises (MSME) (2016) for each catchment, by locating them in the catchments.

Therefore, three different datasets were prepared for industrial water demand to assess sensitivity of the methods.

15.	Water-use rate (urban, rural and livestock populations)	-	NWDA (2016)

Different feasibility studies took different water-use rates as evidenced in the case of both links under study (sub-section 3.4.1). A review of all feasibility reports available at (NWDA 2016) outlines that the most common water-consumption rates used by NWDA are 200, 70 and 50 litres per capita per day for urban, rural and livestock populations respectively which have been used in the present study.

16.	District-based cropped area under different agricultural seasons	-	Open Government Data (OGD) platform (GOI 2016)
17.	El Niño Southern Oscillation (ENSO) datasets (Oceanic Nino Index and Monthly Niño-3.4 index)	-	National Oceanic and Atmospheric administration (NOAA) United States (2016)
18.	Administrative boundaries (Country, State and districts)	-	Hijmans et al. (2015) and India-WRIS (2016)

GIS data are taken from Hijmans et al. (2015). Slight modifications are made using India-WRIS (2016), wherever required.

19.	Climate change data (RCP 2.6 and 8.5) –increase or decrease in rainfall (%)		Chaturvedi et al. (2012).

Thereby, the above-mentioned data were collected, refined and processed to prepare the catchment-based inputs. Any other detail of data processing (wherever needed) is given in the related chapters. Wherever possible, the data were verified from various related reports and/or outputs by other methods.

Further, this thesis used tools which are either freely available in the public domain or suitable free substitutes are available. The main software includes:

1. For geographical data analysis, ArcGIS version 10.3:
   - Used for digitisation, spatial analysis and cartography,
   - Substitutes available, such as QGIS.
2. Catchment and link modelling, Water Evaluation And Planning (WEAP) version 2016.01 - details in Chapter 6:
   - Used for simulation of water availability and demand,
   - Freely available to developing countries and low cost to others.
3. Statistical analysis, SPSS and XL-stat:
   - Used for statistical analysis of data and results,
   - a month free licence (otherwise most of the analysis can be carried out in Microsoft Excel or Open office).

3.4 Study area: ILR links and their catchments

As discussed in Chapters 2, the S-SK and SK-Sr ILR links are intra-state and designed to address WD in the Subarnarekha River basin of Jharkhand state (GoJ-WRD 2016). They are planned to function together using the existing river-channel of South Koel in order to transfer surplus water from River Sankh and River South Koel to the River Subarnarekha (NWDA 2009a; 2009b) (Figure 3.5). Therefore, they are taken as one ILR project in this research and are termed as the Sankh-South Koel-Subarnarekha (S-SK-Sr) link.

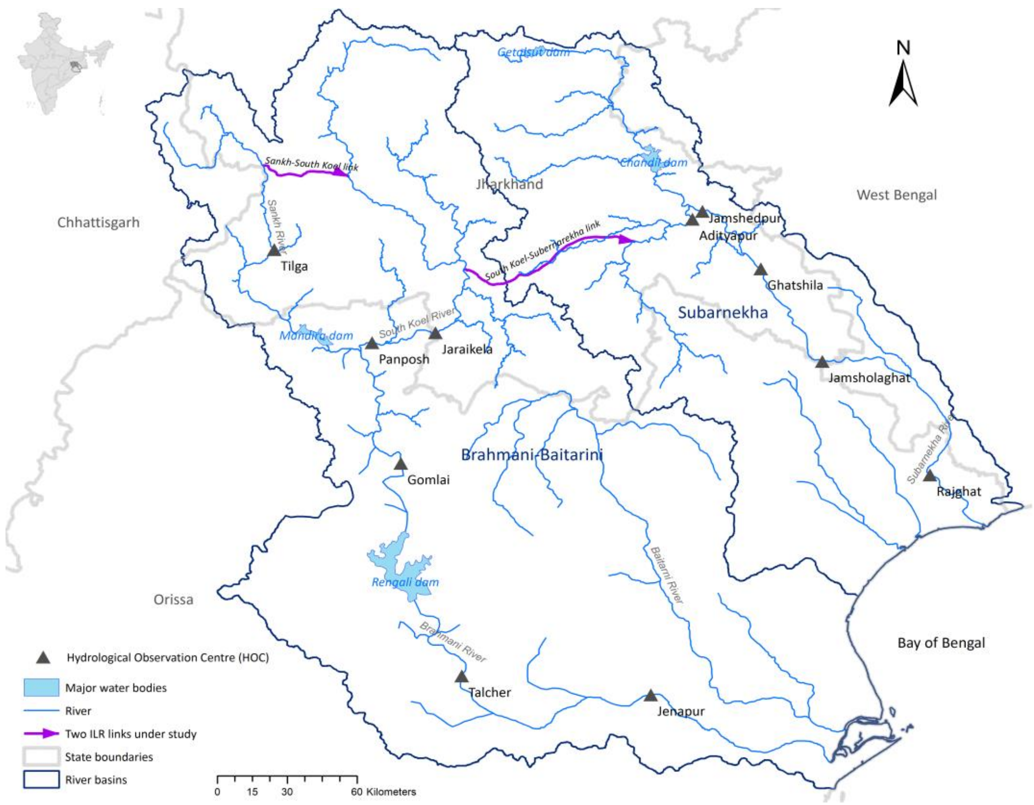


Figure 3.5: 'Sankh-South Koel' and 'South Koel-Subarnarekha' ILR links in their major river basins (Source: NWDA 2009a; NWDA 2009b; India-WRIS 2016)'

The S-SK-Sr link is planned to withdraw a total of 1887 million cubic metres (MCM) [3] of water per annum from two donor rivers, the Sankh and South Koel, tributaries of the River Brahmani flowing in the Upper Brahmani sub-basin of the Brahmani-

[3] This amount includes water reaching to Subarnarekha River (403 and 1281 MCM from River Sankh and River South Koel respectively) and water used *en route* of both links (95 and 108 MCM water for S-SK and SK-Sr link respectively).

Baitarani basin and transfer it to the 'recipient' Subarnarekha River basin through Kharkai River (Figure 3.5). These two ILR links are studied in this thesis for the following reasons:

1. Minimum complexity: The complexity of IBWT projects is discussed in Chapter 2 (section 2.2.2.2). Therefore, care is taken to limit the complexity as much as possible for performing the research within a manageable time-limit. An intra-state ILR link is primarily within the administrative boundary of one state and therefore is managed by one administrative unit. Therefore, it is easier to collect project related information from their planners. Thus being intra-state ILR links, the two links under study are less complex and are managed by the Government of Jharkhand (GOJ) with the help of NWDA of GOI. Moreover, the links are small and their catchments have no other import or export of water, further reducing the complexity of management.
2. Availability of discharge data: As these ILR links are not part of the Himalayan Component of the ILR projects, the related discharge data are available in the public domain.
3. Jharkhand is an underdeveloped state (Mukherjee & Chakraborty 2012) with a large percentage of the population living in poverty (Planning Commission, GOI 2012). Thus, ineffective projects (especially those with significant financial investments) can severely damage the development prospects of Jharkhand, which urgently warrants careful planning of any new project including these proposed ILR projects.

Therefore, these links are ideal for this research and will contribute substantially to Jharkhand and Indian IBWT management.

3.4.1 The ILR links: detail from pre-feasibility reports

As discussed in Chapter 2, the National Water Development Agency (NWDA) prepared pre-feasibility reports (PFR) of both of the ILR two links in 2009 (NWDA 2009a; 2009b) although preparation of detailed progress reports (DPRs) for these links has not yet been undertaken (NWDA 2016a). Following are important details[4] of these links taken from their existing plans.

3.4.1.1 Sankh-South Koel (S-SK) ILR link

The Sankh-South Koel (S-SK) ILR link is 41.2 km long, running along contours (Figure 3.6). The link will be constructed from the River Sankh near Bartoli village, located 250 m upstream of the Jharkhand-Chhattisgarh border. It will join the River South Koel near Bagesera Village of Gumla district.

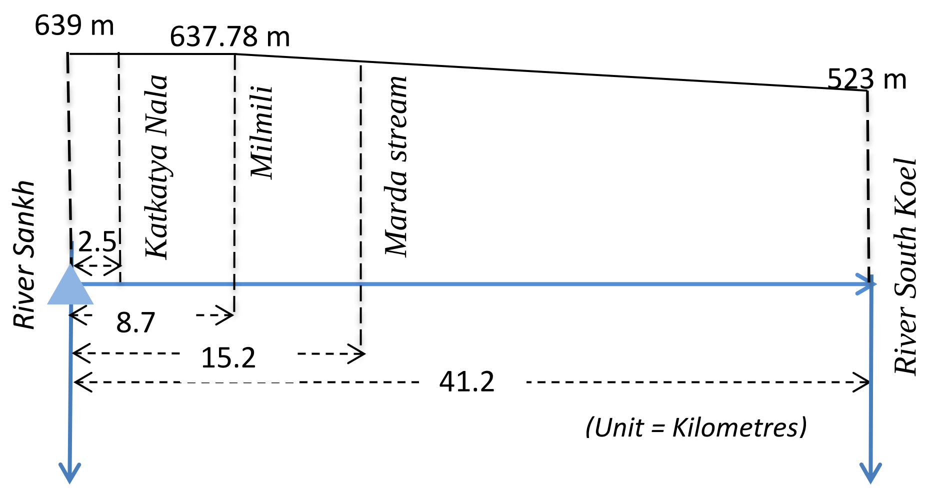


Figure 3.6: Schematic diagram of Sankh-South Koel (S-SK) ILR link based on its pre-feasibility report (PFR) prepared by NWDA (2009a)

A barrage of 750 m length will be constructed at Bartoli with an optimal pond level of 640 m, submerging an area of 1.08 km^2. The difference in elevation between the offtake and outfall points is 116 m which will facilitate three hydro-power installations with capacities of 4, 9 and 15 MW (megawatts) respectively. A silt excluder will operate at the canal's offtake point. The canal will be lined with side-slopes as 1.5H: 1.0V, bed-width 11 m and depth 2.5 m. The canal will be designed to have a mean flow velocity of 0.850 m/s, a design discharge capacity of 33.13 cumec

[4] While describing ILR plans, this thesis has made an effort to keep the details given in the two pre-feasibility reports of the ILR links under study. Several discrepancies were noted in these reports; however they have largely been avoided while writing section 3.4.1 in this chapter and efforts have been made to keep the figures the same as given in the report.

and maximum monthly flow of 112 MCM. The total irrigation command area *en route* is 103.69 km^2 in which 62.21 km^2 is cultivable.

Out of 498 MCM water proposed to be transferred, the link will provide 55 MCM and 30 MCM of water to irrigational and domestic use respectively and it is estimated that around 10 MCM water will be lost in transmission (Table 3.1). The remaining 403 MCM water will be transferred to the Subarnarekha River basin via the South Koel – Subarnarekha ILR link. As stated by NWDA (2009a, p.25), the S-SK ILR link will run throughout the year and its month-wise water transfer plan is given in Table 3.1.

Table 3.1: Month-wise water transfer (in MCM) plan of the Sankh - South Koel ILR link by NWDA (2009b, p.74).

Month	Transmission loss	Water use on the way of S-SK ILR link		Water transfer to Subarnarekha River basin	Total water transfer via S-SK ILR project
		Irrigation	Domestic & Industrial		
June	0.5	1	7	7.5	16
July	1	7	2	55	65
August	1.5	8	2	63	74.5
September	1	6	2	47	56
October	1	4	2	24	31
November	0.5	3	2	15	20.5
December	1	4	2	30	37
January	0.5	3	2	21	26.5
February	1	7	2	52.5	62.5
March	1	8	2	62	73
April	0.5	2	3	12	17.5
May	0.5	2	2	14	18.5
Total	10	55	30	403	498

Water-balance analysis as per the pre-feasibility report (NWDA 2009a)

In the water-balance assessment for S-SK link, NWDA (2009a) considered WA and WD only in the upstream donor catchment covering the catchment of River Sankh up to Bartoli village (Figure 3.7).

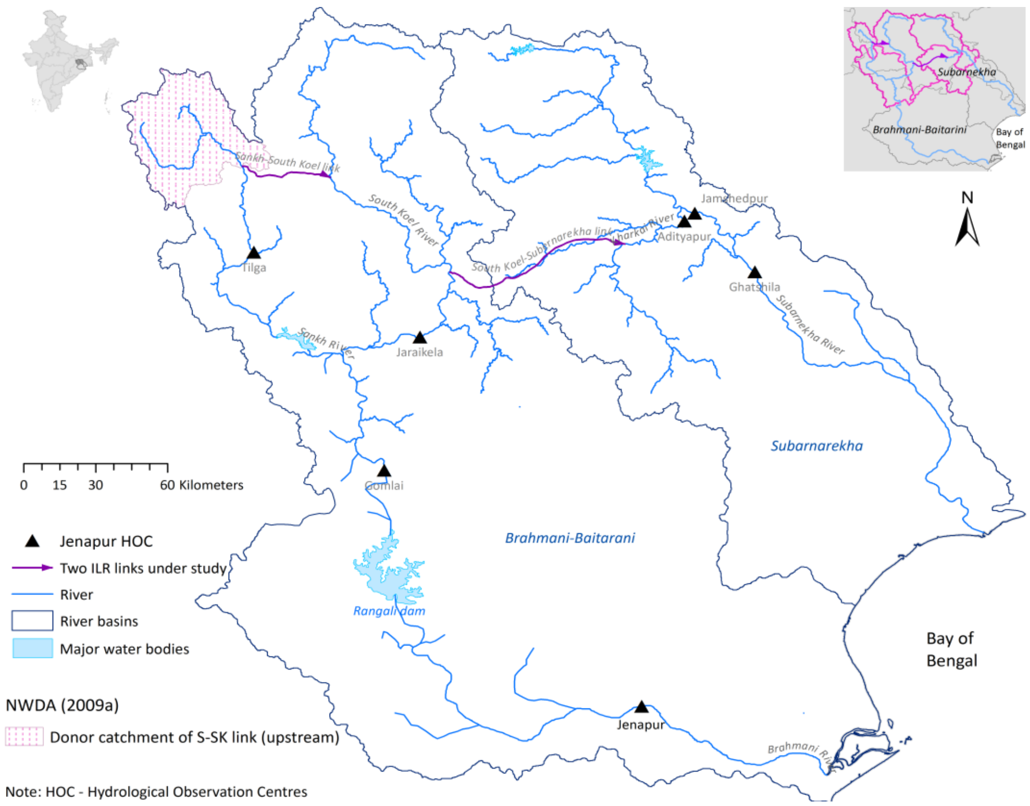


Figure 3.7: Donor catchment of the Sankh-South Koel (S-SK) ILR link within the Brahmani-Baitarani River basin.

For water availability analysis, NWDA (2009a) calculated annual natural water yields[5] at 75% dependability based on Jenapur Hydrological observation centre (HOC) (Figure 3.5) using observed flow data for 34 years (1964-65 to 1997-98). The calculated natural flow was then used to calculate annual WA in S-SK ILR project which is given below. NWDA (2009a) did not consider groundwater availability while assessing the water-balance (per annum) for S-SK link.

Water available at 75% dependability in Brahmani River basin (up to Jenapur HOC)	14851 MCM
Import in Brahmani River basin [future import]	2985 MCM
Total water available in basin including import	17836 MCM

[5] To calculate natural water yield, impact of Rengali reservoir since 1984 is considered. Also, regeneration from upstream water demand for irrigation, domestic and industrial is also taken into account. Regeneration from irrigation is taken as 10% of net irrigated water used after deducting evaporation loss of 10% from major projects and 20% from medium projects. Further, regenerated flow from domestic and industrial water demand are taken as 80%.

Area of entire catchment for Brahmani	39033 km^2
Water available per km^2	17836 / 39033 = 0.4569 MCM/ km^2
Total area of donor catchment (up to Bartoli)	2229 km^2
Water available in donor catchment (up to Bartoli)	2229 x 0.4569 = 1018.5 MCM

To calculate WD, NWDA (2009a) took domestic, irrigation, industrial water demand and a share of committed water utilisation from the Rengali Dam (based on proportionate area) into account. For domestic WD, the ILR plan assumed that the population will stabilise in 2050 A.D. First, NWDA (2009a) calculated the rural and urban population for 2001 based on the proportionate-area method using district-wise population data and added them together to obtain the total population. This estimate was then used to calculate the projected population for the year 2050 using the following equation:

$$P_{2050} = P_{2001} (1 + r/100)^{n}$$

where,
P_{2001} = population in 2001
r = annual population growth rate adopted from UN estimates (1992/1994).
n = number of years
P_{2050} = projected population by end of 2050

Then the percentage of urban population to total population given in UN estimates (1992) was used to project the share of urban population in 2050 (using regression analysis between the year and urban population percentage), which came to 66% of the total population. Then, NWDA (2009a) took 135 and 53.15 litres per capita per day for urban and rural[6] water use respectively and estimated urban and rural WD as 9.15 MCM and 2.37 MCM respectively, totalling 11.52 MCM for domestic need. Further, NWDA (2009a) assumed that 100% of urban WD and 50% of rural WD is fulfilled by surface water. Hence, the total domestic WD for 2050 was

[6] The S-SK PFR did not mention rural water use rate; however, a reversed calculation from one of its tables (NWDA (2009a), table number 2.3 at pg. 13) showed that 53.15 litre per capita per day is used as rural water use rate.

calculated as 10.33 MCM and 80% of it (i.e. 8.26 MCM) accounted for the regenerated flow from it. Further, citing unavailability of industrial WD data, NWDA (2009a) took industrial WD as equivalent to domestic WD i.e. 11.52 MCM and 80 % of it i.e. 9.22 MCM was taken as regenerated flow. For irrigational WD, a cumulative WD of 94.28 MCM from existing projects (20.29 MCM), on-going projects (29.68 MCM) and identified irrigation projects (44.31 MCM) was considered by NWDA (2009a). To calculate the regenerated flow, NWDA (2009a) took 10% of net irrigation water demand i.e. 7.54 MCM[7] after deducting 20% of total irrigational water in evaporation-loss. Further, to calculate the downstream water requirements at the starting point of the S-SK link, only a proportionate-area based share of contribution to Rengali Dam (total 2348.66 MCM capacity) i.e. 139.33 MCM was considered. The livestock population was also projected for 2050 using data for year 2001 with an assumed growth rate of 1%. Using this population and 50 litres per capita per day of water use rate, 13.13 MCM of water demand was determined for livestock. However, NWDA (2009a) assumed this demand to be fulfilled by ground water and therefore did not use it in the water-balance assessment for the S-SK link.

Therefore, the total WD considered in the water-balance assessment for the S-SK ILR link is as follows:

Domestic water demand	10.33	MCM
Industrial water demand	11.52	MCM
Irrigation requirement	94.28	MCM
Downstream commitment for Rengali Dam	139.33	MCM
Total water demand	255.47	MCM

After calculating water availability and water demand, NWDA (2009a) performed a water-balance assessment and reported that 878.77 MCM of water is available (NWDA (2009a, p. II). However, the report did not demonstrate any calculation in its explanation. Using the same calculation given in the ILR plan of SK-Sr link, the present research recreated the calculation for S-SK link which is as follows:

[7] As per S-SK's PFR by NWDA (2009a, pg. 16), the regenerated flow is 7.85 MCM which seems to be miscalculated as it does not match with the other related data and calculation given in S-SK's PFR.

Natural water availability (a)	1018.5 MCM
Total water demand (b)	255.47 MCM
Regeneration from domestic sector (R-Dom)	8.26 MCM
Regeneration from industrial sector (R-Ind)	9.22 MCM
Regeneration from irrigation (R-Irrig)	7.54 MCM
Water available i.e. (a-b) + (R-Dom) + (R-Ind) + (R-Irrig)	788.06 MCM

Therefore, following the recreated calculation, 788.06 MCM water is available at the water transfer point. Out of the total water available, NWDA and GOJ have decided to withdraw 498 MCM (403 MCM for further transfer to the Subarnarekha River catchment via SK-Sr ILR link and 95 MCM for *en route* water use of S-SK ILR link as mentioned above) which is 63.19% of total water available with 75% dependability at Bartoli.

3.4.1.2 South Koel - Subarnarekha ILR link

The South Koel–Subarnarekha (SK-Sr) ILR link is 76.25 km long running along contours and, will take water off from River South Koel near Padyar village, located 30 km upstream of the Jharkhand – Orissa border (Figure 3.8). The outfall is planned to be in the River Kharkai (tributary of River Subarnarekha) at Hurangda Village near Saraikela town. A barrage of 1200 m length will be constructed at Padyar with an optimal pond level of 300 m, submerging an area of 4.37 km^2. The altitude difference between the offtake and outfall points of the SK-Sr ILR link is 118 m which will facilitate four hydropower installations with a total capacity of 100 MW. A silt excluder will function at the junction of the canal. The canal will be lined with side slopes as 1.5H: 1.0V, bed-width 34 m and depth 3 m. The canal will have a proposed mean flow velocity of 1.05 m/s, designed discharge capacity of 125.08 cumec and a maximum monthly flow of 268 MCM. The total command area *en route* is 72 km^2 in which 43.2 km^2 of area is cultivable.

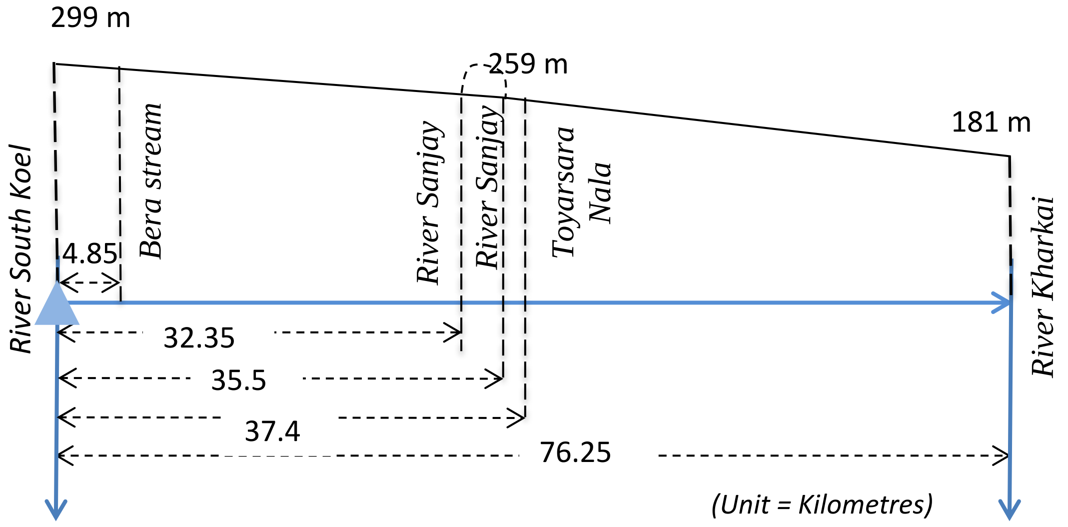


Figure 3.8: Schematic diagram of South Koel-Subarnarekha (Sk-Sr) ILR link based on its PFR by NWDA (2009b).

Out of 1792 MCM of proposed water transfer, the link will provide 38 MCM and 30 MCM of water *en route* to irrigational and domestic use respectively and around 40 MCM water will be lost in transmission (Table 3.2).

Table 3.2: Month-wise water transfer (in MCM) plan adapted from South Koel – Subarnarekha ILR link (appendix 7.10) by NWDA (2009b, pg. 69).

Month (as per Water year in India)	Transmission loss	Water use enroute of SK-Sr ILR link		Water transferred from upstream donor basin of SK-Sr link	Water from S-SK ILR project	Total water transfer via SK-Sr ILR project
		Irrigation	Domestic & Industrial			
June	1	1	7	41	7.5	57.5
July	5	4	2	167	55	233
August	6	6	2	191	63	268
September	4	4	2	144	47	201
October	3	3	2	80	24	112
November	2	2	2	53	15	74
December	3	3	2	95	30	133
January	2	2	2	68	21	95
February	5	5	2	161	52.5	225.5
March	6	6	2	188	62	264
April	1	1	3	45	12	62
May	2	1	2	48	14	67
Total	40	38	30	1281	403	1792

The remaining 1684 MCM water (including 403 MCM water of S-SK ILR project) will be transferred to the water-deficit Subarnarekha River via one of its tributaries, the River Kharkai. As per NWDA (2009b, pg. 22), the SK-Sr ILR link will run throughout the year and its month-wise water transfer plan is given in Table 3.2.

Similar to the S-SK link (NWDA 2009a), NWDA (2009b) considered water availability and demand only in the upstream donor catchment. For the SK-Sr link, it covered River South Koel's catchment area up to Padyar Village (Figure 3.9).

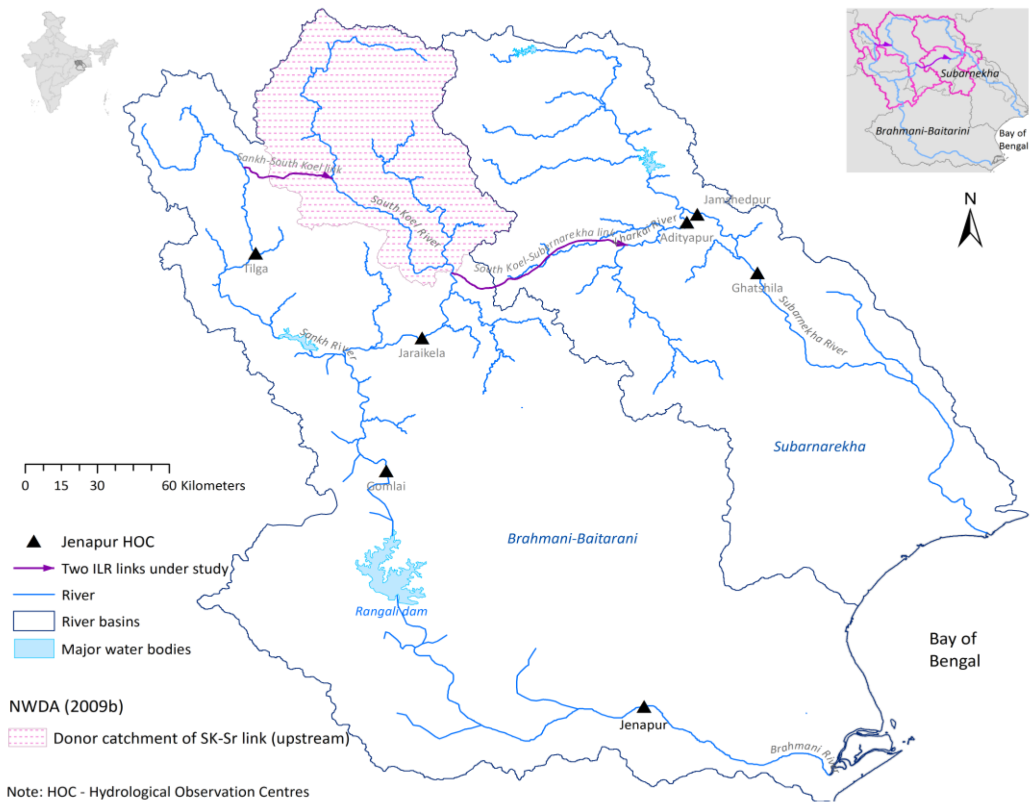


Figure 3.9: Donor catchment of the South Koel-Subarnarekha (SK-Sr) ILR link within the Brahmani-Baitarani River basin.

To assess water availability for the SK-Sr link, NWDA (2009b) used the same method to calculate naturalised river flow on an annual basis at 75% and 50% dependability as used by NWDA (2009a) and used these flows to calculate water availability at Jenapur (Figure 3.5). NWDA (2009b) also used annual water available at 75% dependability for the water-balance assessment (per annum) of SK-Sr link which is as follows:

Water available at 75% dependability in Brahmani River basin (up to Jenapur HOC)	14851 MCM
Import in Brahmani River basin [future import]	2985 MCM
Total water available in basin including import	17836 MCM
Area of entire catchment for Brahmani	39033 km^2
Water available per km^2	17836 / 39033 = 0.4569 MCM/ km^2
Total area of donor catchment (up to Padyar)	7631.25 km^2
Water available in donor catchment (up to Padyar)	7631.25 x 0.4569 = 3487.07 MCM

Similar to the WD calculation for S-SK ILR link, NWDA (2009b) took domestic, irrigation and industrial WD and a share of the contribution to Rengali Dam (based on proportionate area) into account using the same methods. However, some minor differences are noted such as NWDA (2009b) did not mention any water-use rate. A back-calculation from one of its tables (number 2.3) showed that urban and rural water-use rates considered in the ILR plan of SK-Sr are around 216 and 84 litres per capita per day respectively. Urban and rural WD calculated for SK-Sr link are 84.24 MCM and 21.84 MCM respectively, totalling 106.08 MCM for the year 2050. Using the same assumption as before, that 100% of urban and 50% of rural water demand is fulfilled by surface water, total domestic WD was calculated as 95.16 MCM with 80% of it i.e. 76.13 MCM taken as regenerated flow. Industrial WD was 106.08 MCM (equivalent to domestic water demand) and 80% of it i.e. 84.86 MCM, was taken as regenerated flow. Gross cumulative irrigation WD of 939.05 MCM[8] from existing projects (65.49 MCM)[9], on-going projects (146.48 MCM) and

[8] The cumulative water demand is the sum of existing project (65.49 MCM), on-going projects (146.48 MCM) and identified irrigation projects (706.65 MCM) which is actually 918.62 MCM; however page 12 of PFR by NWDA (2009b) reports it to be 939.05 MCM. Therefore, 939.05 MCM of irrigational water demand is taken.

[9] As per page 11 of SK-Sr's PFR by NWDA (2009b), the total water demand for existing irrigation project is 65.49 MCM; however as per its appendix (2.8), the total water demand for existing irrigation project is 63.89 MCM.

future irrigation projects (706.65 MCM)[10] was considered and 10% of net irrigation WD i.e. 73.49 MCM was taken as regenerated flow[11] after deducting evaporation-loss from gross irrigational WD. However, the existing plan for S-SK link prepared by NWDA (2009b) reported the regenerated flow to be 65.60 MCM and considered it in the water-balance assessment. Downstream water requirement at the offtake of the SK-Sr link was estimated as 475.86 MCM. The livestock WD of 22.09 MCM was also calculated in a similar way as for the S-SK link but NWDA (2009b) too did not consider it in the water-balance assessment.

Therefore, total WD considered in the water-balance assessment for the SK-Sr ILR link is as follows:

Domestic water demand	95.16 MCM
Industrial water demand	106.08 MCM
Irrigation requirement	939.05 MCM
Downstream commitment for Rengali Dam	475.86 MCM
Total water demand	1616.15 MCM

Several discrepancies are noted in the water-balance assessment of the SK-Sr link by NWDA (2009b, pg.8-12). However, the current research endeavours to keep the reporting as close as possible to the source documents. The detailed water-balance assessment given in NWDA (2009b) is as follows:

Natural water availability (a)	3487.07 MCM
Total water demand (b)	1616.15 MCM
Regeneration from domestic sector (R-Dom)	76.13 MCM
Regeneration from industrial sector (R-Ind)	84.86 MCM
Regeneration from irrigation (R-Irrig)	65.60 MCM[12]
Water available i.e. (a-b) + (R-Dom) + (R-Ind) + (R-Irrig)	2097.51 MCM[13]

[10] As per page 11 of SK-Sr's PFR by NWDA (2009b), the total water demand for existing irrigation project is 706.65 MCM; however as per its appendix (2.8), the total water demand for existing irrigation project is 660.95 MCM.

[11] As per S-SK's PFR by NWDA (2009b, pg. 12), the regenerated flow is 65.60 MCM which seems to be miscalculated as it does not match with the other related data and calculation given in SK-Sr's PFR.

[12] As given in SK-Sr's PFR (NWDA 2009b, pg.12) although as per calculations based on data and methodology given in SK-Sr's PFR, it should be 73.49 MCM as mentioned in page 10.

In this way, 2097.51 MCM of water is estimated to be available at the offtake point of the SK-Sr ILR link. Out of the total estimated water available, NWDA and GOJ has decided to withdraw 1389 MCM (1281 MCM water will be transferred to Subarnarekha River and 108 MCM water will be used *en route*) which is 66.22% of total water available with 75% dependability at Padyar.

3.4.2 The catchments of the ILR links under study

As mentioned above, the existing plans of the S-SK and SK-Sr links only assessed the upstream donor catchments in their decision-making (Figure 3.7 and Figure 3.9). However, as discussed in Chapter 2, globally accepted criteria-sets for IBWT advise that any such project should consider both donor and recipient catchments in their decision-making (Chapter 2, section 2.2.4). Therefore, the current research delineated the donor and recipient catchment areas affected by the two links (Figure 3.10) keeping following conditions in mind:

1. As mentioned in Chapters 1 and 2, the links are intra-state, therefore they lie within one state and follow an administrative boundary for their management. However, for water management, hydrological units[14] are the more sensible units (GWP 2009); therefore in this thesis, they are used to determine the study area instead of the administrative boundary of Jharkhand state.
2. Due to the constraints of scale, data and time-period for undertaking PhD research, the study area is restricted within the catchment area affected most by the ILR links. To delineate this area, methods similar to Gurung & Bharati (2012) were used which observed that the immediate downstream catchments are most affected. Therefore, this research has included the immediate downstream donor and recipient catchments in the study.

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[13] NWDA (2009b, pg. 12) reported it to be 2097.51 MCM taking water availability as 3487.48 (7631.25 x 0.457 = 3487.07 MCM). The present work uses the original figure as given in the case of Sankh-South Koel (page 4).

[14] Globally basin, catchment, watershed are interchangeable in different countries and disciplines (GWP 2009); but GOI takes basin as the major hydrological unit which is further divided into sub-basins and then in watersheds.

3. ILR plans used flow data available at Jenapur HOC (Figure 3.5), which is farther from the two water withdrawal points, despite the latest and longer period daily discharge data available at nearby HOCs (India-WRIS 2016). Data available at these HOCs could facilitate better water availability assessments (Loucks et al. 2005). Therefore, six of these HOCs (Tilga, Jaraikela, Gomlai, Adityapur, Jamshedpur and Ghatshila) are selected to delineate the catchments in study area (Figure 3.10).

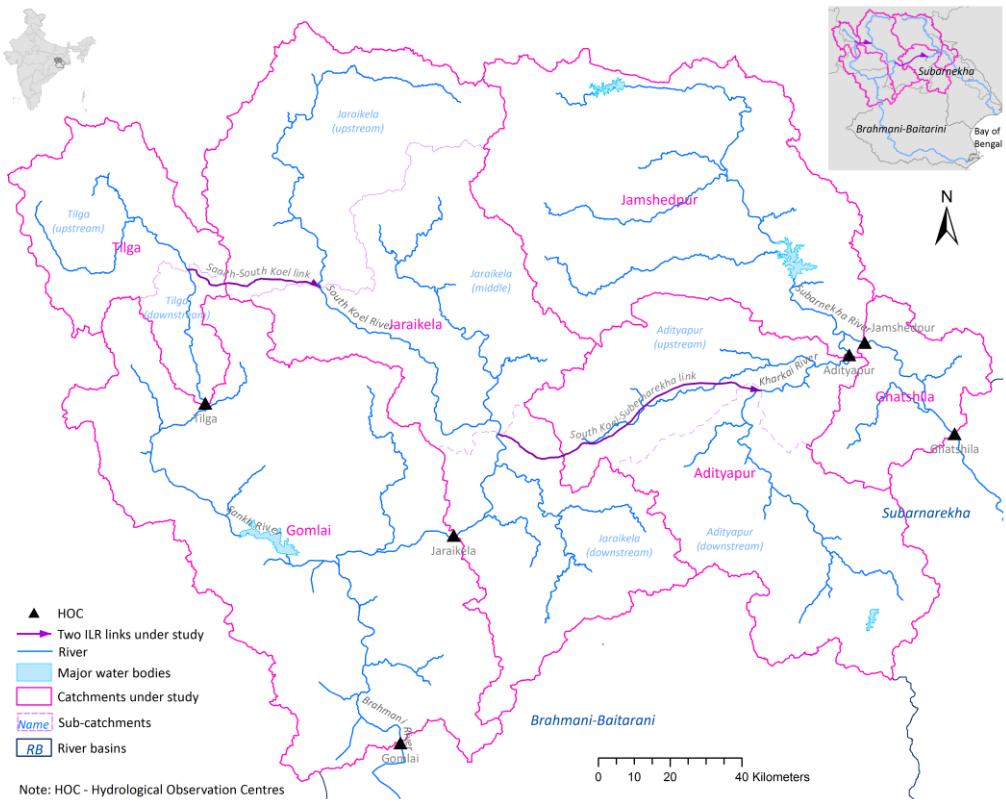


Figure 3.10: The study area delineated on the basis of six Hydrological Observation Centres (HOC) selected as per Gurung & Bharati (2012) along with their sub-catchments as per the two Inter-linking of Rivers (ILR) projects.

The catchments for these HOCs are delineated by void-filled Digital Elevation Model (DEM) at 3 arc-second (~90 metres) prepared under HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales) project based on datasets from the Shuttle Radar Topography Mission (SRTM)[15] by the United States Geological Survey (USGS) (USGS 2007). In this research, the catchments are

[15] SRTM DEM has been extensively used by GOI in its Water Resource Information System i.e. India-WRIS (India-WRIS 2016).

named after their HOCs. These derived catchments represent the study area based on recommendations by Gurung & Bharati (2012). Three of these catchments, namely Tilga, Jaraikela and Adityapur, are further divided into sub-catchments on the basis of offtake and outfall locations of the two ILR links under study (Figure 3.10). During the analyses carried out in this thesis, these catchments and sub-catchments are grouped as donor and recipient as well as upstream and downstream catchments and sub-catchments for each link (S-SK and SK-Sr links) for the joint project (S-SK-Sr).

As mentioned above, the existing plans by NWDA (2009a, 2009b) only covered the project area within the Jharkhand state (Figure 3.2). However, when globally accepted IBWT criteria-sets are taken into account, the area affected by projects expands beyond the boundary of Jharkhand State (Figure 3.11).

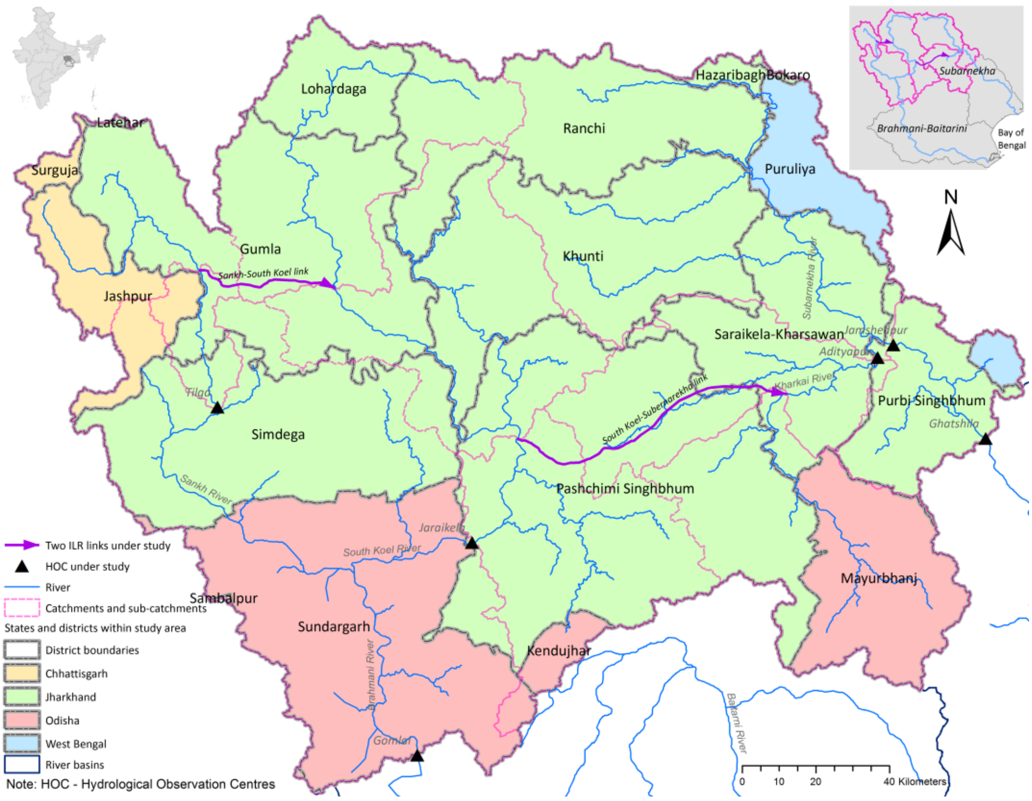


Figure 3.11: Administrative boundaries of the states and districts within the study area (Data source: Hijmans et al. 2015)

Although the study area still covers a large part of the Jharkhand state, it also covers parts of Chhattisgarh, Odisha and West Bengal states. Figure 3.11 presents the administrative boundaries within the study area at the state and district level.

3.5 Summary

This chapter has briefly described the methodological approach taken in this research which has five major components, each dealing with one of the objectives of this thesis. Due to the large scale of study and the diversified range of ensemble methods, finer details of data and methods are explained in the chapters where they are used. Further, the chapter provided a set of premises which was used to collect and process the datasets used in the current research and produced a data-inventory. It was followed by the list of major software tools used in this research. Then, the chapter provided details of the two ILR links under study including their location and existing plans by NWDA. It was followed by the explanation for the delineation of catchments under study. It was noted that the project area assumed by the existing ILR planners is smaller than the project area delineated by this using the IBWT criteria-sets.

Chapter 4 Characterisation of the catchments

4.1 Introduction

Chapter 4 provides a holistic and multi-disciplinary understanding of the catchments involved in the Sankh-South (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR projects. It describes the landscape characteristics and explores important hydrological and socio-economic factors of the catchments involved in the two ILR links under study. Section 4.2 of this chapter explains the methods used and section 4.3 describes the landscape characteristics of the study area. Section 4.4 evaluates rainfall and flow to understand hydrological patterns while section 4.5 explores socio-economic trends in the catchments. Section 4.6 discusses and compares these different patterns between the donor and recipient catchments.

4.2 Materials and Methods

4.2.1 The donor and recipient catchments

Chapter 3 (section 3.4.2) outlined that the study area is based on the catchments of six hydrological observation centres (HOC) namely Tilga, Jaraikela, Gomlai, Adityapur, Jamshedpur and Ghatshila (Figure 4.1) and covers the immediate catchment area of S-SK and SK-Sr ILR links. Further, it has been explained that the two ILR links are planned to function together via existing river channels; therefore, they are taken as one project, the Sankh-South Koel-Subarnarekha (S-SK-Sr) ILR project, in this thesis. On this basis, the six catchments are grouped as donor and recipient catchments (Figure 4.1). The total catchment area under study is 35,963 km^2 and covers two major river basins: the Brahmani-Baitarani and the Subarnarekha river basins.

The catchments of the Tilga, Jaraikela and Gomlai are part of the Brahmani Sub-basin of the Brahmani-Baitarani River basin (India-WRIS 2012) and form donor catchments (Figure 4.1). When mentioned collectively in this chapter, they are termed as the ‘donor basin’. The flow of the River Sankh in the Tilga catchment (observed at Tilga HOC) and the flow of the South Koel river in the Jaraikela catchment (observed at Jaraikela HOC) contribute to the flow observed at Gomlai HOC (River Brahmani).

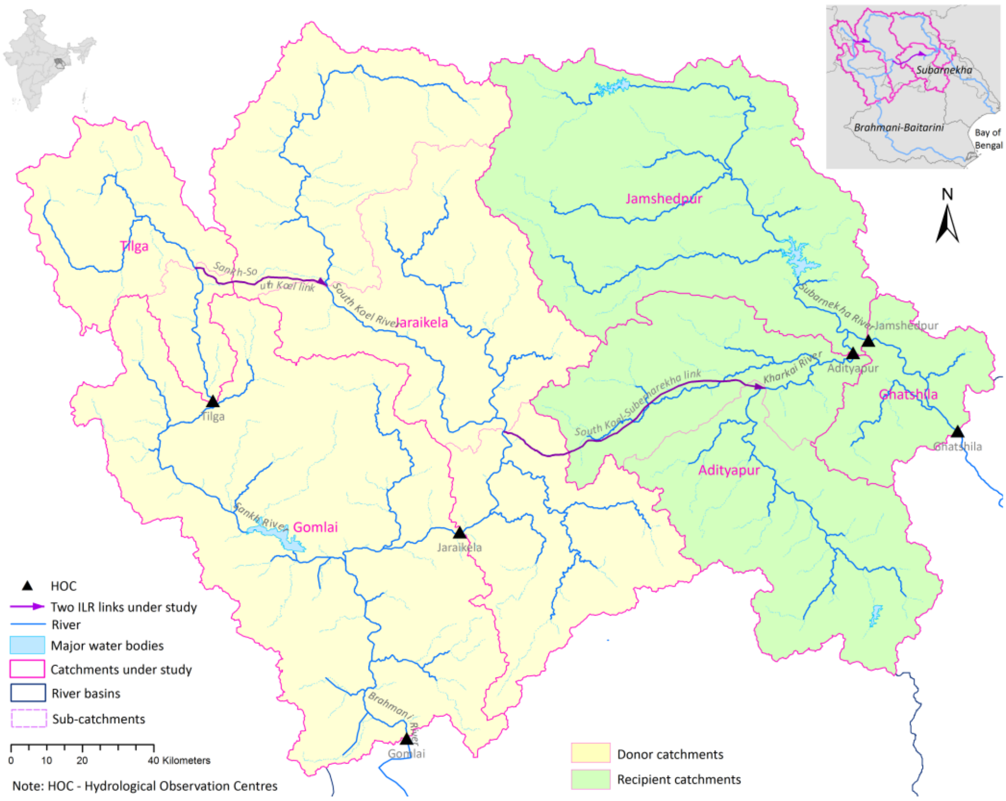


Figure 4.1: The six catchments (donor and recipient) under study along with their hydrological observation centres (HOC) and sub-catchments following the two Inter-linking of rivers (ILR) projects.

The catchments of Jamshedpur, Adityapur and Gomlai are part of the Subarnarekha River basin (India-WRIS 2012) and form the recipient catchments (Figure 4.1). When mentioned collectively in the chapter, they are termed as the ‘recipient basin’. The flow of the River Kharkai in the Adityapur catchment (observed at Adityapur HOC) contributes to the flow observed at Jamshedpur HOC (River Subarnarekha), which further contributes to the flow observed at Ghatshila HOC (River Subarnarekha).

4.2.2 Method

The datasets used in the present research are listed in the following flow chart (Figure 4.2). Their details are presented in Chapter 3 (section 3.1). The methods used in this chapter are part of the second methodological components of this research and are outlined in Figure 4.2. They broadly cover: landscape characterisation, hydrological behaviour and socio-economic patterns.

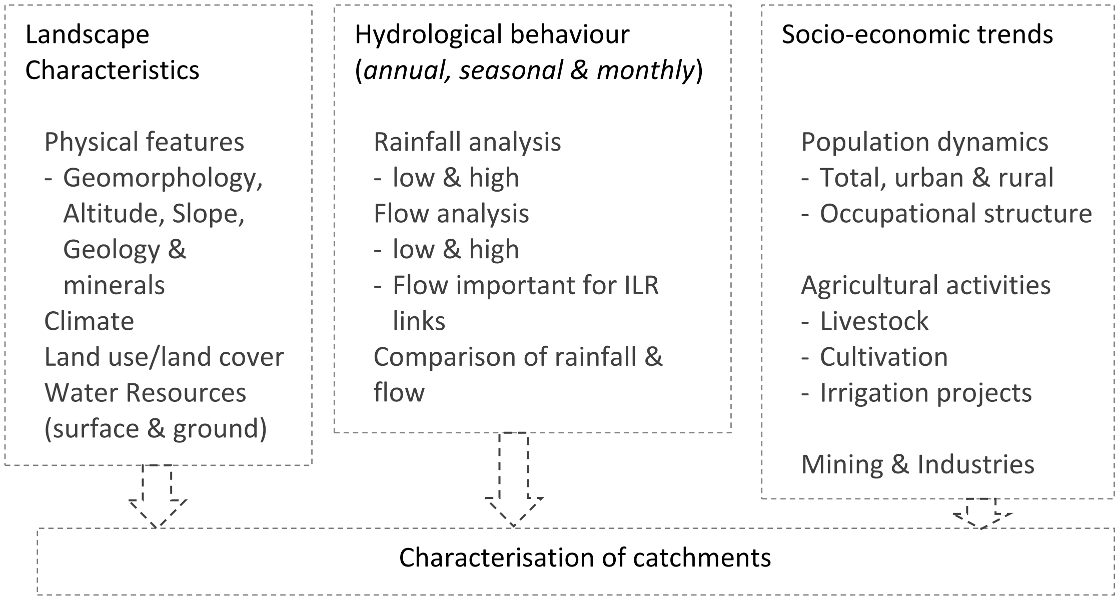


Figure 4.2: Flow chart of the methods used in the characterisation of the catchments.

4.2.2.1 Landscape characterisation

To understand the current status of catchments under study (Figure 4.1), first, physical landscape characteristics (climate, geomorphology, geology, minerals, land use & land cover, and water resources) were compiled from different government reports (including the feasibility studies of the ILR links) and then assessed in order to understand the physical features prevalent in the catchments under study. Studies by Colby (2003), Biggs et al. (2007) and Loucks et al. (2005) are used for guidance.

4.2.2.2 Hydrological behaviour

Understanding hydrological characteristics of the catchments and analysing any temporal change in them are prerequisites for the planning and management of their water resources (Yue et al. 2002). Therefore, the hydrological behaviour of all six catchments was assessed individually and comparatively (Gaál et al. 2012) using analysis of daily rainfall (mm) (1971-2005) and daily mean flow (cumec) (1979-2013).

Both rainfall and flow datasets of all catchments were checked for normality (Shaw & Wheeler 1994) using the Shapiro-Wilk (W) test (detail in Shapiro & Wilk 1965), Jarque-Bera (JB) test (detailed in Jarque & Bera 1980) and Q-Q plot (Scott 2016). The W statistic is based on the correlation between observed data and its corresponding normal score (Ghasemi & Zahediasl 2012). The JB statistic is based on sample skewness and sample kurtosis based on the original data and examines their normal distribution (Newbold et al. 2013). W is recommended as one of the best normality tests by Ghasemi & Zahediasl (2012); however, its sample size is limited to 2000 (Royston 1992). The JB statistic uses a large number of samples and is good for large datasets (Filliben & Heckert 2015). Further, a visual normality test using Q-Q plots was also carried out as advised by Ghasemi & Zahediasl (2012) for both datasets: without any transformation, transformed using natural log (Wang & Vrijling 2005), and transformed using the cube-root method (Cox 1999). Following the check for normally distributed data, both rainfall and flow datasets of all catchments were checked for any significant non-stationarity in order to decide if they required simple stationary stochastic or complex deterministic models to represent the processes (Lins 2012). The Student *t* test (details in Machiwal & Jha 2012), the Augmented Dickey-Fuller (ADF) proposed by Said and Dickey (details in Rutkowska & Ptak 2012) and the KPSS test (details in Wang & Vrijling 2005) proposed by Kwiatkowski, Phillips, Schmidt and Shin (Rutkowska & Ptak 2012) were performed to determine if there was any substantial non-stationarity indicating a change in the mean and variance of the two datasets with time (Lins 2012).

After normality and stationarity tests, both rainfall and flow datasets for all catchments were analysed at the annual and seasonal scale (monsoon and non-monsoon) for the following:

- Descriptive statistics
- Patterns: spatial and temporal; Influence of El Niño
- Trends (sudden and gradual)

– Relationship of rainfall and flow

Descriptive

Descriptive statistics provided basic understanding of the rainfall and flow in the catchments (Bracken et al. 2008) which included mean, minimum, maximum, standard deviation, coefficient of variation, skewness, kurtosis, percentile and quantile.

Patterns

Spatial patterns of rainfall and flow were determined using correlation (Pearson Correlation coefficient). To analyse spatial patterns of flow, the flows across catchments were compared by their water yield (flow per square kilometre). This was followed by analyses of temporal patterns in mean rainfall and flow along with their autocorrelation (Shaw & Wheeler 1994; Triola 1998). The impact of El Niño was assessed through cross-correlation between monthly rainfall and flow datasets, and Oceanic Niño Index (ONI) to examine the long-term pattern of wet and dry years, thus drought and flooding (Krishnamurthy & Goshwami 2000). ONI is a three-month moving average of the monthly Niño-3.4 index (an anomaly calculated from the 30-year mean sea-surface temperature (°C)); a three-month moving average rainfall (mm) and flow dataset were used for this cross-correlation.

Trends

High and low magnitude events of rainfall and flow are good indicators of change in the hydrological regime and their numbers and magnitude could be used as indices to assess any change in the hydrological behaviour of the catchments (Morán-Tejeda et al. 2012). Therefore, to detect any temporal change in the hydrological regime, indices given in Table 4.1 (based on Morán-Tejeda et al. 2012; NWDA 2009a; 2009b; Reddy 2005) have been assembled using mean daily rainfall and mean daily flow, and then examined.

Table 4.1: Rainfall and flow indices used in present study.

Rainfall Indices
Low rainfall -
1. Number of dry days (rainfall < 2.5 mm (Rao 1979) [1]) per year
2. Number of days with precipitation < = mean rainfall per year
High rainfall -
3. Number of days with precipitation > 90th percentile per year
4. Maximum daily rainfall (annual and seasonal) per year
Flow indices
Low flow -
5. Minimum flow per year
6. Flow under < 1 percentile per year and their number of days
7. Flow under < 10th percentile per year and their number of days
Flow important for ILR project in India -
8. Flow under < 25th percentile per year and their number of days
High flow indices -
9. Flow over > 90th percentile per year and their number of days
10. Flow over >95th percentile per year and their number of days
11. Maximum flow per year

The change in the hydrological regime could be either sudden or slow; sudden change depicts marked but occasional change in regime, while slow change (trend) shows a change in regime that is "likely to continue" (Villarini et al. 2009, pg. 2). Hence, all datasets have been analysed to delineate types of temporal change using non-parametric statistical measures the: Pettitt test (Pettitt 1979), Mann-Kendall *tau* and Spearman's *rho* (Villarini et al. 2009; Yang & Tian 2009).

The *Pettitt test* is based on the Mann-Whitney two-sample rank-based test which assists in detecting unknown abrupt changes in the median (detailed in Pettitt 1979). Abrupt change points are critical and ignoring such change points can mislead any trend analysis as significant trends can be observed despite the absence of any statistically significant trend in the time-series before and after the change point (Villarini et al. 2009). Therefore, the Pettitt test was used in the present research to detect any sudden change point in rainfall and flow datasets. The series of datasets which showed significant abrupt change points were

[1] Morán-Tejeda et al. (2012) used threshold of < 1 mm for dry days in his study area (Spain). However, Rao (1979) used threshold of < 2.5 mm in similar study in India. Therefore, in the present research a threshold of <2.5 mm has been used.

subsequently divided into two subseries by using their respective sudden change points (Villarini et al. 2009) and were called *before period* and *after period* series.

Mann-Kendall tau and *Spearman's rho* were used to assess gradual change i.e. the trend in the rainfall and flow datasets (mean, minimum, maximum and indices mentioned above). Mann-Kendall *tau* (detailed in Mann 1945) examines trends in a variable with time (Wang & Vrijling 2005). Spearman's *rho* (detailed in Yue et al. 2002) can also be used to examine temporal trends; used in hydro-metrological studies (Villarini et al. 2009). Mann-Kendall *tau* is the commonly preferred test for trend analysis while Spearman's *rho* has been used occasionally (Yue et al. 2002). Yue et al. (2002) outlined that little information is available on which test is more appropriate in a given situation and noted that both tests have similar powers to detect trends. Villarini et al. (2009) used both tests to get a better indication of trends. Therefore, the present research used both the 'Mann-Kendall *tau* and Spearman's *rho*' tests to provide greater certainty in any trends observed.

Before performing the Mann-Kendall *tau* and Spearman's *rho*, the datasets were examined for the serial autocorrelation effect (von Storch & Navarra 1995) as positive serial correlation could affect the variance of Mann-Kendall *tau* and therefore could influence its results. It was examined by using the Lag-1 serial correlation coefficient r_1 (Gocic & Trajkovic 2013). If r_1 is significant at the 5% level then the time-series needs to be pre-whitened (Gocic & Trajkovic 2013). To pre-whiten any series, r_1 is subtracted from the time-series and then the Mann-Kendall *tau* test is performed on the resultant pre-whitened time-series (Wang & Vrijling 2005).

Relationship of the rainfall and flow

The relationship of rainfall and flow was assessed within the catchments by a visual comparison of their patterns as well as cross-correlation between them.

4.2.2.3 Socio-economic trends

Socio-economic dynamics influence water resources in any catchment therefore, these dynamics need to be assessed for better water resource planning and management (GWP 2009). Among socio-economic dynamics, population dynamics are major factors and affect water availability through direct and indirect consumption (Iglesias et al. 2007). The most important factors are agriculture and irrigation (Rosenzweig et al. 2004), livestock (Amarasinghe et al. 2008) and industry activities (van Rooijen et al. 2009). Therefore, these socio-economic factors have been analysed in the present research which includes population (total, urban and rural) for year 2011, occupational structure (2011), agricultural activities (2006-2012) including livestock (2012) and industrial activities.

4.3 Landscape characterisation

4.3.1.1 Physical features

Among the six catchments under study (Figure 4.1), Jaraikela is the largest catchment (10,472 km^2) followed by Gomlai (8,704 km^2), Jamshedpur (6,428 km^2), Adityapur (6,245 km^2), Tilga (2,630 km^2) and Ghatshila (1,485 km^2). The study area is extensively covered (66%) by a series of plateaus in step-form known as Chotanagpur plateaux (CGWB 2015) (Figure 4.3). The upper plateau area, in the north-west of the catchment, is known as the Pat region. It is 750-1100 m above mean sea-level (MSL) (NWDA 2009a, 2009b) and covers 54% of Tilga. It is followed by the Ranchi-Hazaribagh plateau (600-750 m above MSL) covering 38% of Tilga, 36% of Jaraikela and 19% of Jamshedpur catchment. The Lower Chotanagpur plateau (300–600 m MSL) follows these two plateaux and covers a larger part of all other catchments than the Tilga and Ghatshila. The plateaux are dotted with inselbergs and denuded hills (CGWB 2015) and are separated by scarps giving it the form of ‘steps’ (NWDA 2009a, 2009b).

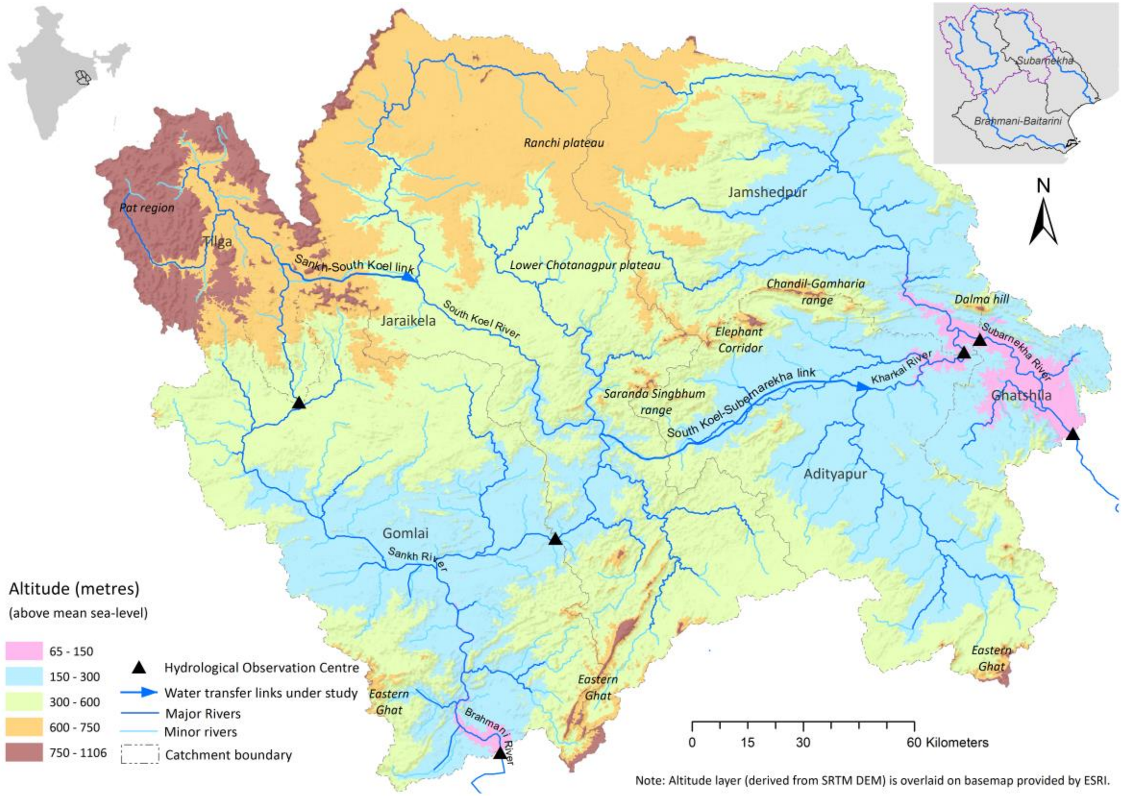


Figure 4.3: Altitude and main geomorphological features of study area.

The area surrounding the plateaux (150 – 300 m above sea-level) which forms 32% of the study area, is uneven; it consists of rock outcrops, plains and river valleys (CGWB 2015). Adityapur catchment has 58% of its area in this category and is followed by 41% of Gomlai and 42% of Jamshedpur catchments. Only 2% of the catchment area is below 150 m (above sea-level), covering most of Ghatshila catchment. The southern part of the study area (Gomlai catchment) covers parts of the denuded Eastern Ghat (Houlton 1949).

Since the study area is in a plateau region, the majority of the area has a gentle slope up to 5% and about 80% of area has a slope <12%. The presence of scarps, dotted hills and inselbergs has resulted in the presence of moderate to high slopes in all catchments (Figure 4.4).

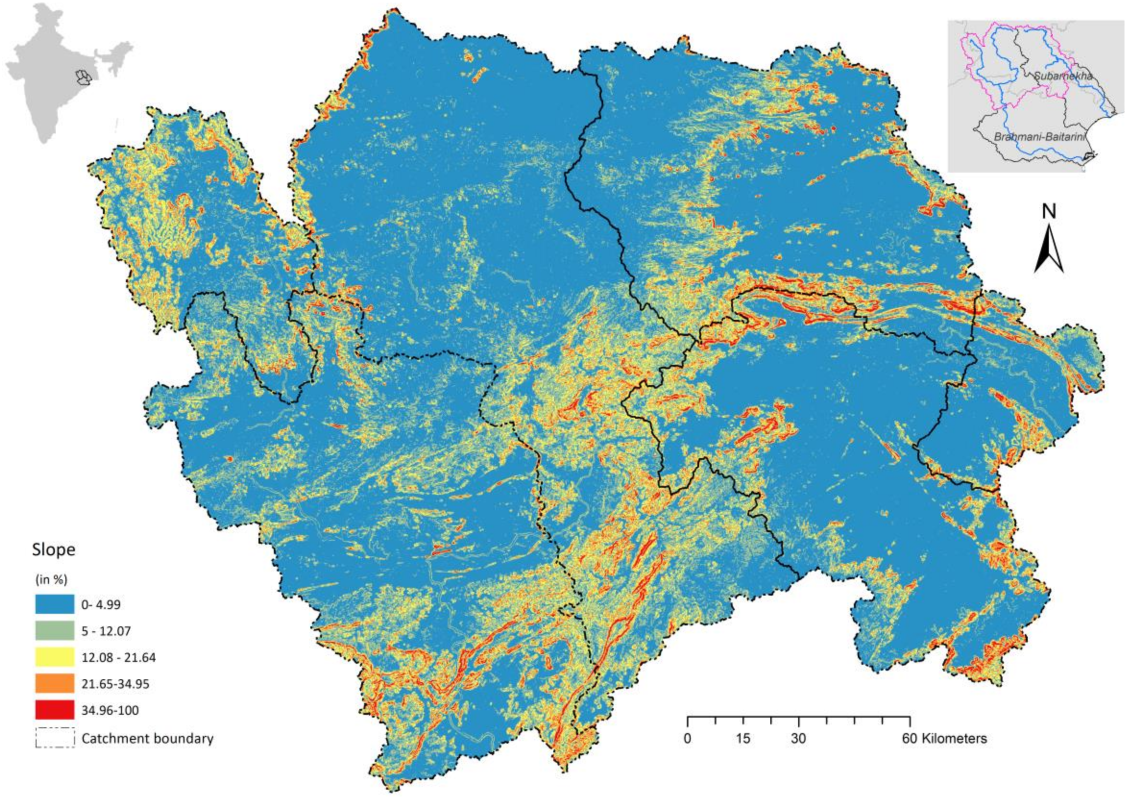


Figure 4.4: The slope characteristics in the study area.

The study area is diverse in geological nature (Figure 4.5). The majority of the area (approximately 79% of total study area) falls in the Indian shield which is constituted of Precambrian rocks such as granite, gneisses, quartzite, schist, charnockite and Gondwana rocks such as shale and sandstone (Sundaray, 2010; Gautam et al., 2015). The area upstream of Adityapur and in the south-west of the Ghatshila catchments consists of Singbhum-Orissa craton primarily made up of Archean rocks and rea. The area under the Eastern Ghat mountains in the Gomlai catchment is formed of crystalline rocks (Sundaray 2010). Recent alluvium of the Tertiary and Quaternary periods is found in some northern-most upstream areas of Jaraikela, Jamshedpur and Tilga catchments and in the southern-most part of the Gomlai catchment (NWDA 2009a; CGWB 2014). Due to the geological formation, the study area covered by the Singbhum-Orissa craton (which is located in Adityapur and Ghatshila) is rich in minerals such as iron, manganese, limestone, bauxite, asbestos, gold, chromite, apatite, barytes, dolomite, copper, uranium, vanadium, kyanite, fire clay etc. (Geogical Survey of India (GSI) 2010; Panda et al. 2005) (Figure 4.45).

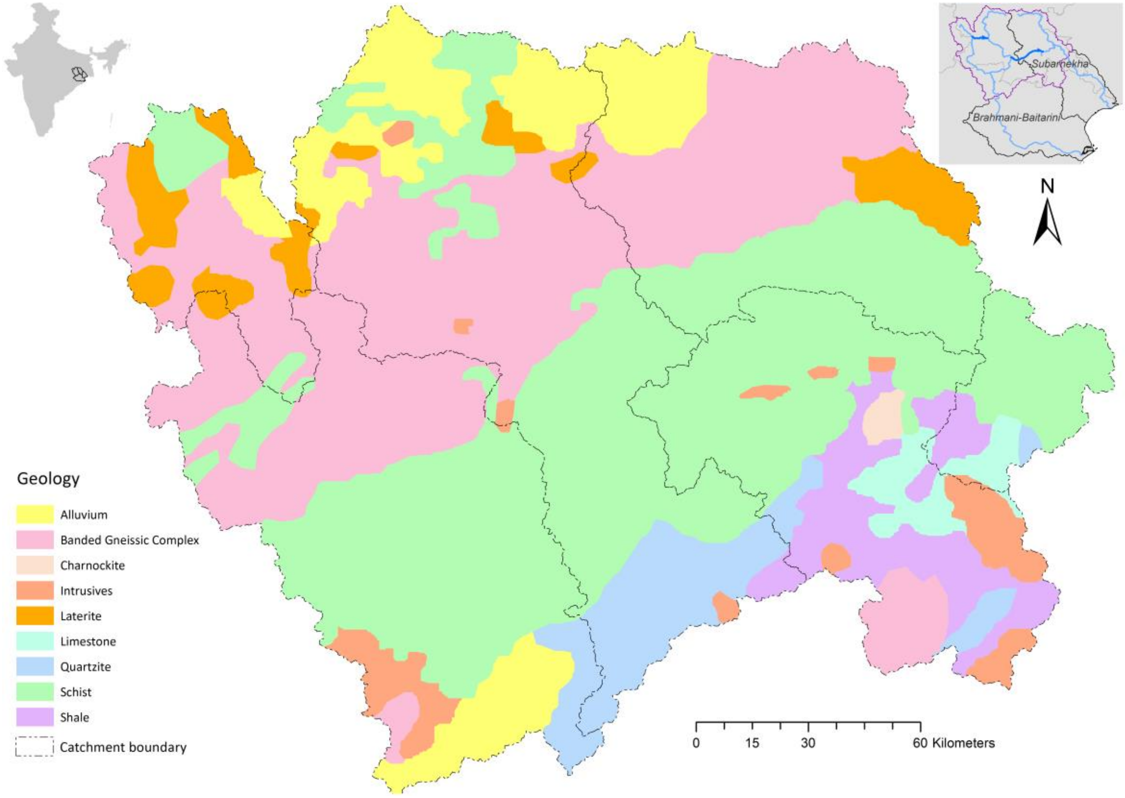


Figure 4.5: Geology (and lithology) of the study area (CGWB 2014)

The soil in the study area has a high iron content (CGWB 2015). The soil type is mainly residual and red soil is most common (CPSP 2005; CGWB 2015) especially in areas with metamorphic rocks (gneiss, schist and quartzite) (Figure 4.5). It is sandy and loamy with a low water-holding capacity and poor fertility (CGWB 2015). Lateritic soil is another poorly fertile soil, commonly found in the hilly and plateau regions of the study area. Alluvial soil is deposited over consolidated rocks mainly in river valleys and can also be found in patches away from valleys; their thickness is controlled by the regional topography which affects the fertility (CGWB 2015). Some parts of the lowlands in the Ghatshila catchment have black soil which is highly fertile (CGWB 2015).

4.3.1.2 Climate

The study area has a hot-humid climate and monsoonal rain (Rawat et al. 2016). The average annual temperature (1971-2000) of the study area is 24.9 °C, spatially ranging from 24.3°C to 25.5°C (Figure 4.6). The average monthly temperature ranges from 18°C – 30.8°C (Figure 4.8). May is the hottest, while January is the coldest month. The maximum and minimum temperatures are 41°C (Gomlai catchment) and 8.7°C (Tilga catchment) respectively.

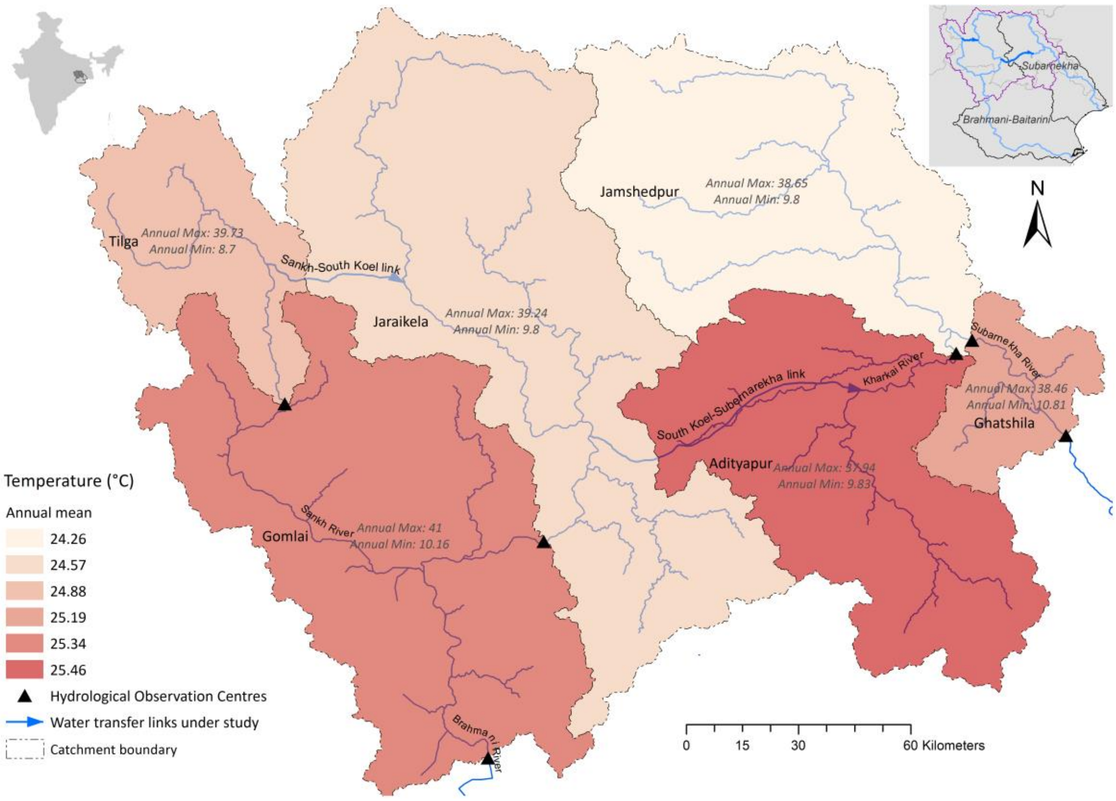


Figure 4.6: Mean, maximum and minimum daily temperatures of catchments in a year (Source: India-WRIS 2016)

The area receives rainfall from south-westerly monsoon systems (Rao 1979). The mean annual rainfall for the whole study area (1971-2005) is 1367 mm; however for donor basins it is 1391 mm, while for recipient basins it is 1330 mm. Among the catchments rainfall ranges from 1458 mm (Tilga catchment) to 1311 mm (Jamshedpur catchment) (Figure 4.7). Monthly total rainfall ranges from 8.5 mm (December) to 339 mm (July) (Figure 4.8) with most rainfall occurring in monsoon months (86-91% of total annual). The annual rainfall variability increases towards the west (Figure 4.7). Section 4.4.1 discusses the rainfall of study area in detail.

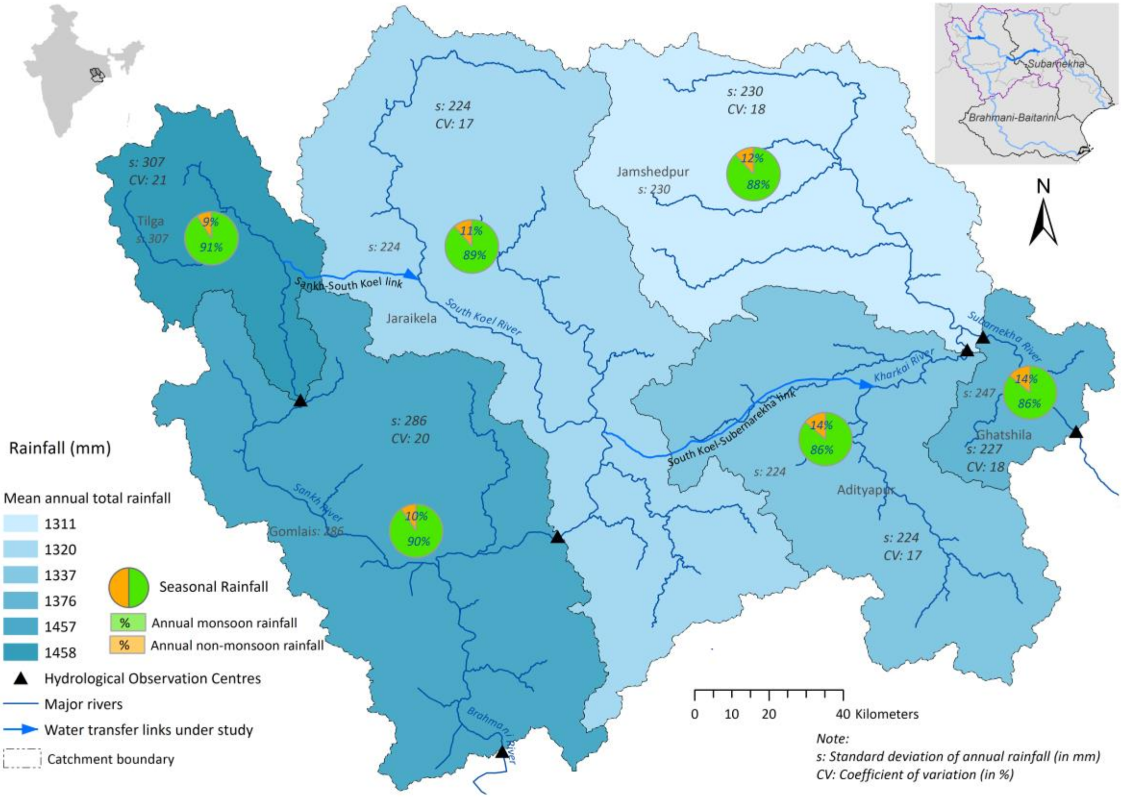


Figure 4.7: Mean annual and seasonal rainfall along with annual variability (standard deviation (S) and coefficient of variation (CV)) in study area.

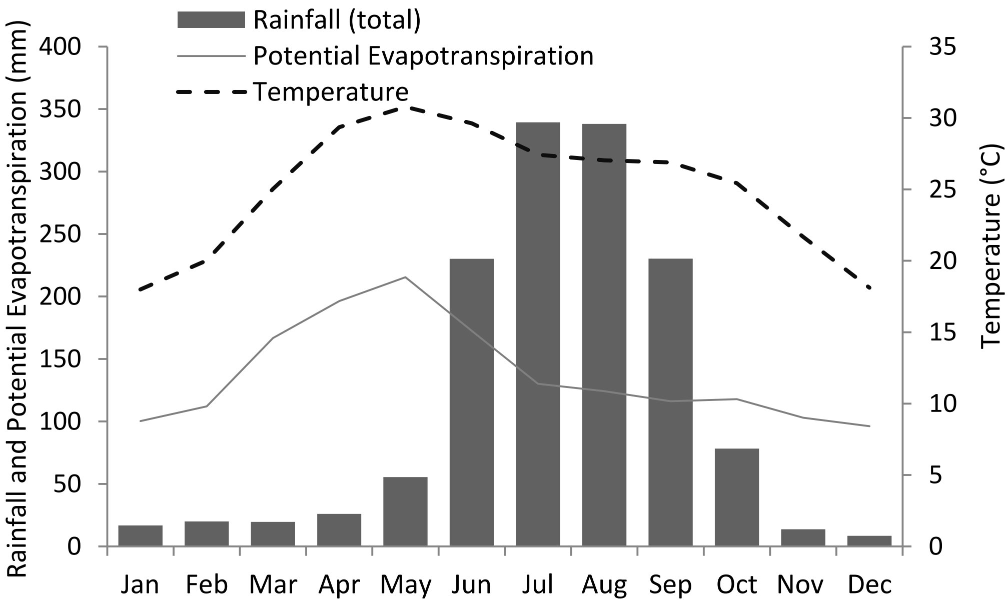


Figure 4.8: Mean temperature, rainfall and potential evapo-transpiration (PET) of the study area on monthly basis.

Further, the mean annual potential evapotranspiration (PET) of the study area ranges from 1587 to 1694 mm and is highest in Gomlai followed by Ghatshila, Adityapur, Jamshedpur, Jaraikela and Tilga (Figure 4.9). During the monsoon monthly PET is less than the rainfall despite the high temperatures, but in non-monsoon months, higher PET is observed (Figure 4.8).

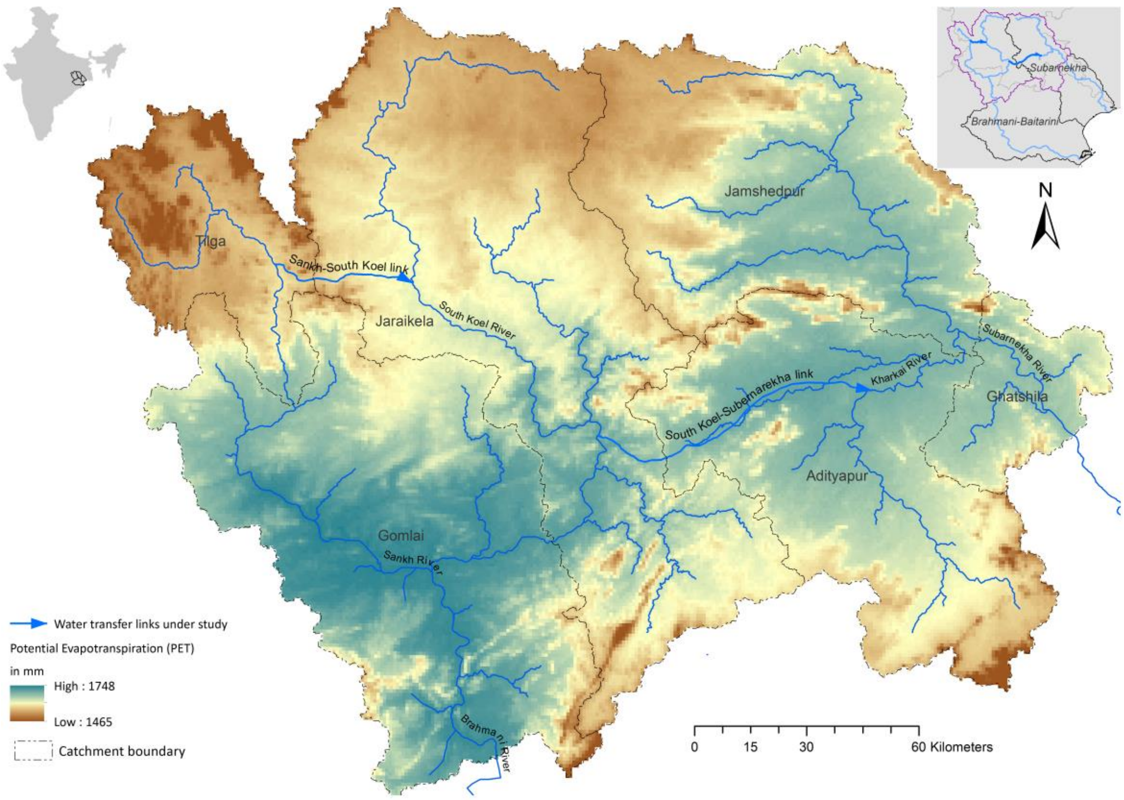
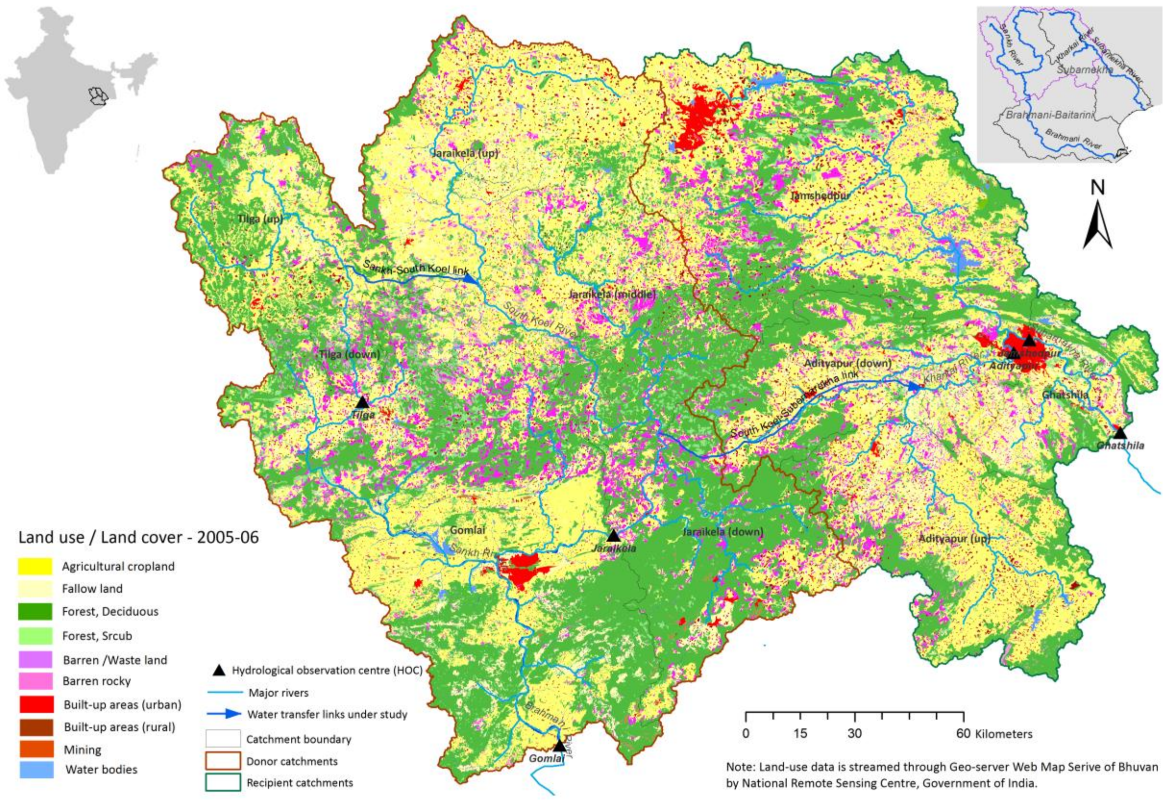


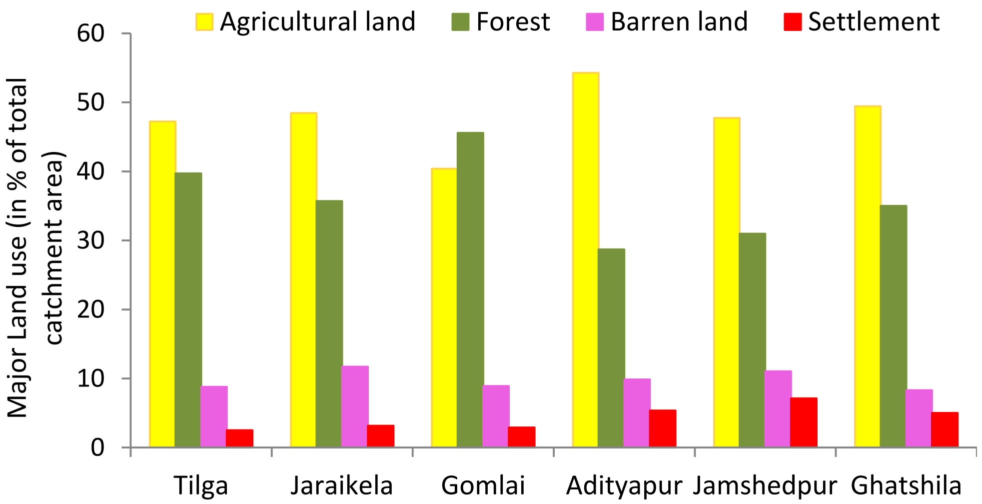
Figure 4.9: Mean annual potential-evapotranspiration (PET) in study area (Source: CGIAR-CSI, Zomer et al. 2008).

4.3.1.3 Land use

The study area falls in a 'sub-tropical humid' ecological zone (Sehgal et al. 1992). The majority of the areas are forested (36.3% during 2005-06) (Figure 4.10a) and are dominated by deciduous broad-leaf trees (Rawat et al. 2016). Among all catchments, Gomlai has the maximum extent, while Adityapur has the minimum extent of forest (Figure 4.10b and Table 4.2a). Overall the donor catchments have more forested areas than the recipient catchments as evident in Figure 4.10b and Table 4.2b. The area under agriculture is similar in all catchments with the greatest area found in Adityapur and the least in Gomlai (Figure 4.10b).



(a)



(b)

Figure 4.10: Land use of study area (2005-2006): (a) Land use map and (b) percentage of major land use in total catchment area (Source: India-WRIS 2015)

The cropland percentage is highest in Jamshedpur while least in Ghatshila (Table 4.2a; Figure 4.42). Overall, recipient catchments have more land under agricultural use (Table 4.2.b). Further, although the area is rich in minerals (MoC&I, GOI 2016), the land used for mining and industry is not visible in Figure 4.10a and accounts for only 0.2% of the total area (see section 4.5.3 for details). The percentage of area under settlement is higher in the recipient catchments and highest in Jamshedpur. Tilga has the least amount of settlement. Both urban and rural areas are higher in the recipient catchments (Table 4.2b). Barren land accounts for a similar percentage in all catchments.

Table 4.2: (a) Land use (2005-06) of individual catchments, (b) donor and recipient catchments along with whole study area (India-WRIS webGIS 2015).

(a) Land use	Catchment (area in in km^2)					
	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Cropland	618	3139.0	2324.9	2151.2	2405.0	174.7
Fallow land	623	1934.5	1189.5	1238.7	664.0	559.0
Forest, Deciduous	979.3	3438.5	3537.6	1674.3	1729.3	439.9
Forest, Scrub	65.2	300.5	430.0	118.1	261.4	80.0
Barren/Waste land	199.7	1086.9	725.4	567.6	672.8	105.2
Barren rocky	31.5	140.2	49.5	48.8	36.5	18.2
Built-up (urban)	6.2	41.9	91.8	53.0	192.4	27.3
Built-up area	60.1	290.4	161.4	282.7	266.4	47.1
Mining (& industry)	0.5	20.8	21.8	3.4	11.0	1.1
Water bodies	45.0	79.1	171.7	107.8	189.3	32.1
Total	2629.5	10471.6	8703.7	6245.5	6428.1	1484.7

(b) Land use	Donor catchments (Tilga, Jaraikela and Gomlai)		Recipient catchments (Jamshedpur, Adityapur and Ghatshila)		Whole Study area	
	In km^2	In %	In km^2	In %	In km^2	In %
Agricultural cropland	6082.1	27.3	4730.9	36.3	10813.0	30.1
Fallow land	3747.8	15.3	2461.7	13.7	6209.5	17.3
Forest, Deciduous	7955.4	38.6	3843.5	26.9	11798.9	32.8
Forest, Scrub	795.7	4.3	459.5	3.3	1255.2	3.5
Barren /Waste land	2012.0	8.8	1345.5	10.0	3357.5	9.3
Barren rocky	221.3	0.8	103.6	0.6	324.8	0.9
Built-up area urban)	139.8	0.9	272.7	2.2	412.5	1.1
Built-up area (rural)	511.9	2.1	596.2	4.3	1108.1	3.1
Mining (& industry)	43.1	0.2	15.5	0.1	58.6	0.2
Water bodies	295.8	1.7	329.3	2.5	625.1	1.7
Total	21805	100	14158	100	35963	100

4.3.1.4 Water resource

According to the Planning Commission of GOI (Singh 2006), the study area is rich in water resources. At 75% flow dependability, around 6.1 billion cubic meters (BCM) and 3.1 BCM per year water leave the donor and recipient basins (Table 4.3).

Table 4.3: Surface water availability in the catchments (MCM) (details in section 4.4)

Catchments	Annual Surface water availability (MCM) at 75% dependability	
	Naturalised flow[2]	Observed flow
Tilga	1254	1211
Jaraikela	2679	2463
Gomlai	6925	6142
Adityapur	1671	1266
Jamshedpur	6313	3294
Ghatshila	6327	3125

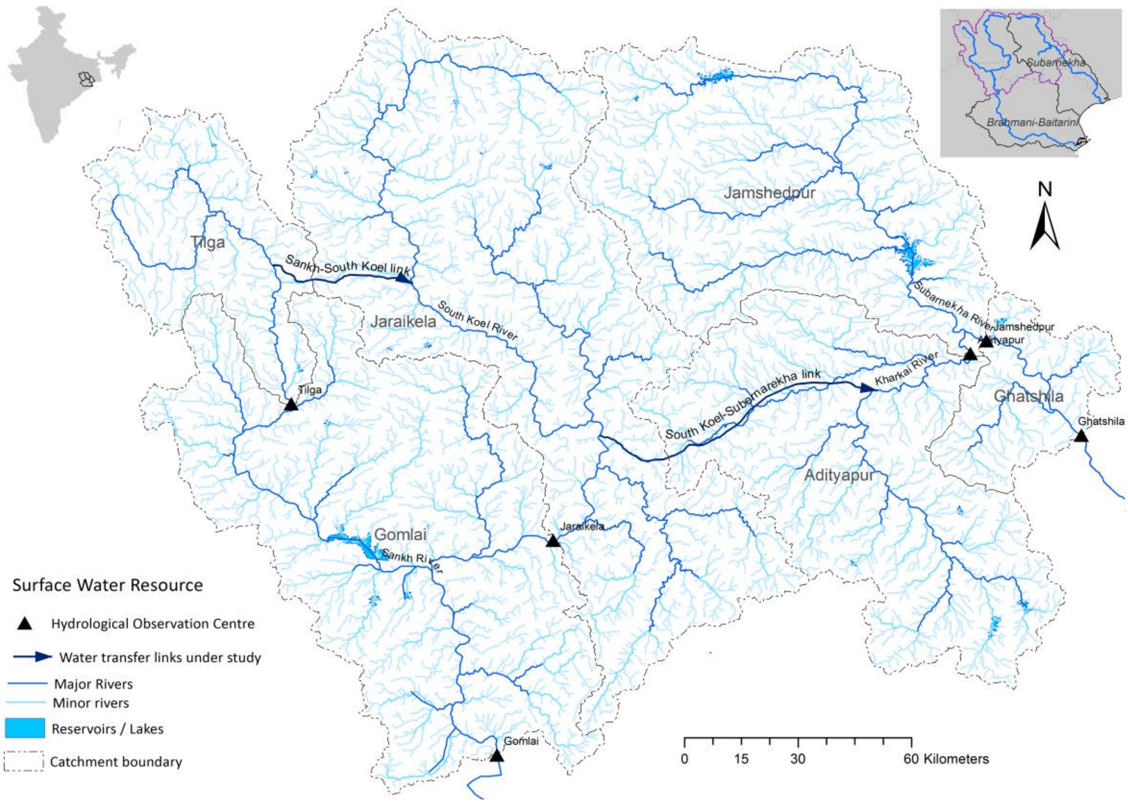


Figure 4.11: Surface water bodies in the study area along with the proposed ILR links.

[2] See section 5.2.1.2 for details

Both donor and recipient basins have dendritic drainage pattern (Figure 4.11). Most of the water is available during monsoon months (see section 4.4). Surface water resources are more developed in the recipient basin (see section 4.5.2) as evident from the comparison of water availability through natural[3] and observed flow (Table 4.3).

On the other hand, based on CGWB (2014), the donor and recipient basins showed net ground water availability of 1.51 BCM and 1.1 BCM respectively in 2011 (Table 4.4). Their respective annual ground water draft (ground water permissible to use based on the recharge rate of the region) were 0.42 and 0.26 BCM (Table 4.4). WR-GOJ (2012) which covers three-fourth of the total study area also reported similar net ground water availability in 2012 (Appendix B.1).

Table 4.4: Net ground water availability, annual ground water draft and recharge rates in the catchments for the year 2011 (based on CGWB 2014).

Catchments	Net ground water availability (in MCM)	Annual ground water draft (MCM) based on stage[4] (%)	Area (%) under ground-water recharge rate (m/year)		
			< 0.1	0.1-0.25	> 0.25
Tilga	202	70	48.9	51.1	0
Jaraikela	655	185	93.3	6.7	0
Gomlai	659	167	47.8	52.2	0
Adityapur	520	156	53.1	46.9	0
Jamshedpur	460	91	70	0	30
Ghatshila	125	17	100	0	0
Donor	*1516*	*422*	*69.8*	*30.2*	*0*
Recipient	*1104*	*263*	*65.5*	*21.3*	*13.2*
In total area	2621	685	68.1	26.7	5.2

Overall, permissible ground water use amounts to 5.7% and 4% of total water available in the donor and recipient basins (CGWB 2014) as given in Table 4.5.

[3] The details related to natural water availability is given in Chapter 5.
[4] The stage of ground water development (%) is a ratio of annual groundwater draft and net annual ground water availability (CGWB 2015b).

Table 4.5: Total water availability in the catchments (MCM) with percentage of ground water in it which can be used.

	Total water available (WA) including natural surface water at 75% dependability and ground water permissible to use (in MCM)	Percentage of ground water which can be used out of total WA
Tilga	1324	5.3
Jaraikela	2864	6.5
Gomlai	7347	2.3
Adityapur	1827	8.5
Jamshedpur	6404	1.4
Ghatshila	6590	0.3
Donor	*7347*	*5.7*
Recipient	*6590*	*4.0*
In study area	13937	4.9

4.4 Hydrological behaviour

The rainfall and flow datasets were examined for normality using the Shapiro-Wilk (W) test (Shapiro & Wilk 1965), Jarque-Bera (JB) test (Jarque & Bera 1980) and Q-Q plot (Scott 2016) and then for stationarity (Lins 2012). Their results presented here are with confidence (α) 0.005. Both W and JB demonstrated non-normality of rainfall and flow datasets (significance levels (ρ) < 0.0001). Q-Q plots also indicated non-normality in all three cases: without any transformation, transformation using natural log, and transformation using the cube-root method. When examined for stationarity, all three tests taken (the Student t test (Machiwal & Jha 2012), the Augmented Dickey-Fuller (ADF) (Rutkowska & Ptak 2012) and the KPSS test (Wang & Vrijling 2005)) found both datasets to be stationary (ρ < 0.001). However, here it should be noted that even if datasets related to natural processes (e.g. hydrological datasets) show stationarity, they have non-stationarity in their nature as they are continuously changing under several mechanisms such as longer-term climate trends (Lins 2012). Therefore, Rutkowska & Ptak (2012) refer to the stationarity of hydrological datasets as 'weak stationarity'.

Further, rainfall and flow datasets of all catchments were assessed at annual and seasonal scale for their descriptive details, spatial and temporal pattern, sudden and gradual change, and their relationship with each other. The results are detailed below.

4.4.1 Rainfall

4.4.1.1 Annual

Figure 4.7 showed the spatial distribution of mean annual rainfall among the six catchments and provided the basic rainfall facts (section 4.3). Table 4.6 provides an overview of annual rainfall data for all catchments. Among the six catchments, Tilga and Gomlai exhibited the highest annual rainfall with the highest rainfall variation (Table 4.6).

Table 4.6: Descriptive statistics of annual rainfall (mm) (1971-2005)

Annual rainfall		Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Total years		35	35	35	35	35	35
Mean		1458	1320	1457	1337	1311	1376
Median		1494	1300	1481	1311	1320	1342
Standard deviation		307	224	286	224	230	247
Coefficient of variation (%)		21	17	20	17	18	18
Range		1557	1067	1560	868	985	1102
Minimum		889	850	773	876	871	809
Maximum		2446	1917	2333	1744	1856	1911
Skewness		0.75	0.42	0.46	-0.01	0.31	0.13
Kurtosis (excess)		1.95	0.72	1.79	-0.72	-0.15	-0.25
Percentiles	10	1078	1033	1163	1040	1028	1075
	25	1200	1161	1267	1139	1147	1179
	50	1494	1300	1481	1311	1320	1342
	75	1603	1464	1607	1527	1503	1555
	90	1818	1619	1842	1637	1604	1722

Even median rainfall, an important descriptor for hydrological datasets (Shaw & Wheeler 1994) is higher in Gomlai and Tilga and so is the annual rainfall (Table 4.6 and Figure 4.12). Jamshedpur and Ghatshila also have similar rainfall; however they differ markedly at the higher end of the annual rainfall range (75^{th} and 90^{th} Percentile). Median rainfalls of all three recipient catchments are similar to that of Jaraikela, the main donor catchment; however, they are less than Tilga and Gomlai (Table 4.6). Skewness of annual rainfall (total) for all catchments except Tilga is between -0.5 to +0.5 and indicates nearly symmetrical distribution (GraphPad 2016) (Table 4.6). Similar to McNeese (2016) positive Kurtosis (excess) for donor catchments indicates that their annual rainfalls have ‘heavier tails’ which is not the case for recipient catchments. This indicates the influence of extremes which is also corroborated by Figure 4.12. Recipient catchments have a similar average and spread of data while donor catchments differ markedly (Figure 4.12).

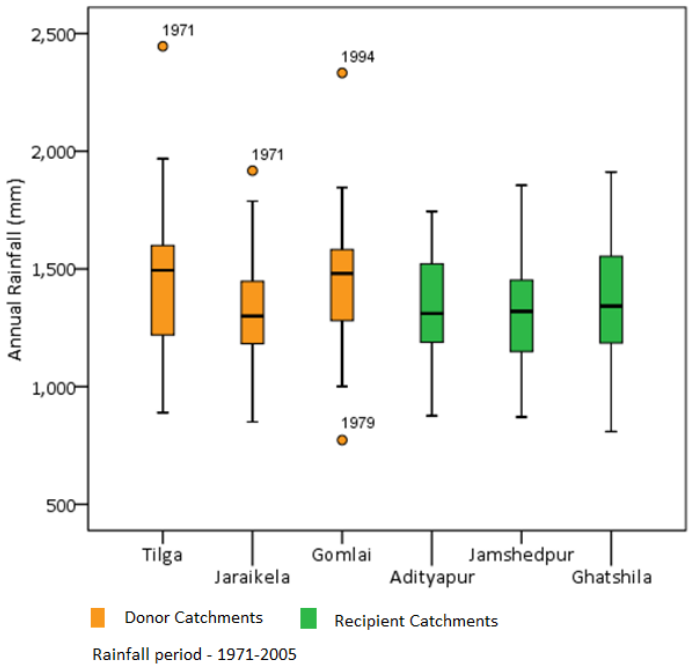


Figure 4.12: Box plot of annual rainfall (mm) in the six catchments during 1971-2005.

Overall, rainfall is similar across catchments which are indicated by their significant correlation coefficients; however, donor and recipient basin-wise patterns are evident (Table 4.7).

Table 4.7: Correlation (Pearson Correlation) of annual rainfall in the catchments.

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.856**	1				
Gomlai	.719**	.781**	1			
Adityapur	.592**	.798**	.706**	1		
Jamshedpur	.679**	.794**	.662**	.857**	1	
Ghatshila	.607**	.737**	.623**	.902**	.828**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 4.13: Annual rainfall (mm) pattern along long-term mean annual rainfall.

Figure 4.13 shows the temporal variation of annual rainfall during 1971-2005 along with the five-year moving average rainfall for all catchments. It highlights that catchments exhibit similar rainfall patterns; however they differ slightly between donor and recipient catchments. Further, Figure 4.13 shows alternate wet and dry cycles of 1-3 years in all catchments, which are also evident when explored at a monthly resolution (Figure 4.14). Further, another cycle of extremely dry years of 9-12 years (1979, 1989-90, 1999-2000) is also evident (Figure 4.13 and Figure 4.14).

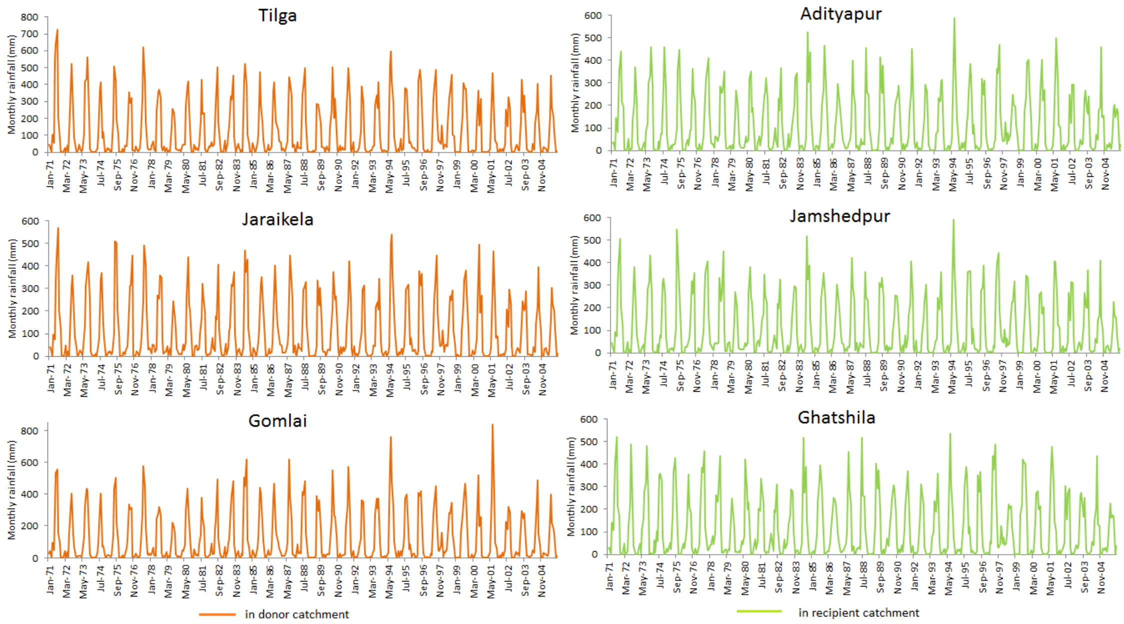


Figure 4.14: Monthly rainfall (mm) in all catchments during 1971-2005

When examined using autocorrelations, these cycles can be seen although they are statistically insignificant except in two cases (Figure 4.15). Ghatshila showed a significant short-term cycle while Jaraikela showed a significant long-term cycle. Extremely dry year cycles may be caused by the impact of El Niño (Krishnamurthy & Goshwami 2000); therefore the relationship between rainfall and El Niño was examined by cross-correlating rainfall and the Oceanic Nino Index (ONI) at monthly scale. Tilga showed statistically significant negative correlation between the rainfall and ONI with a lag of 6-7 months between them (Figure 4.16). The same cross-correlation and lag were observed in other catchments; however, the relationship was moderately significant for Gomlai and weak for the rest of the catchments.

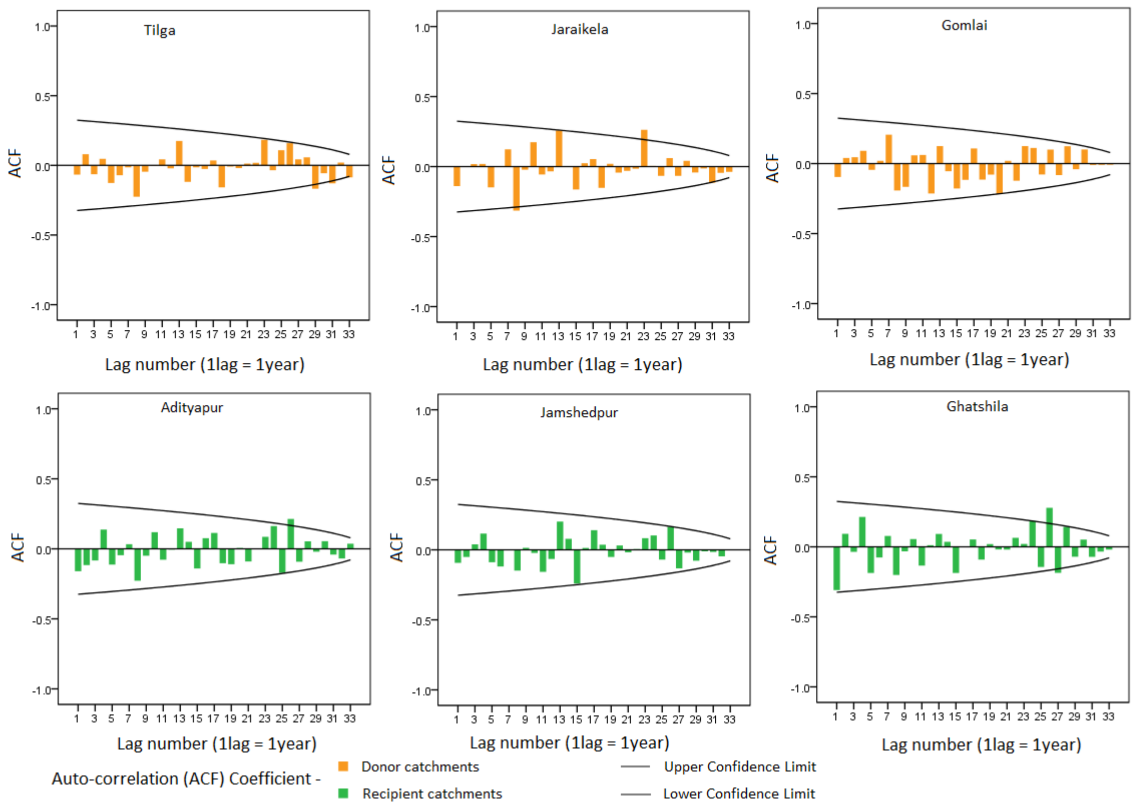


Figure 4.15: Auto-correlation (ACF) of annual rainfall in the catchments.

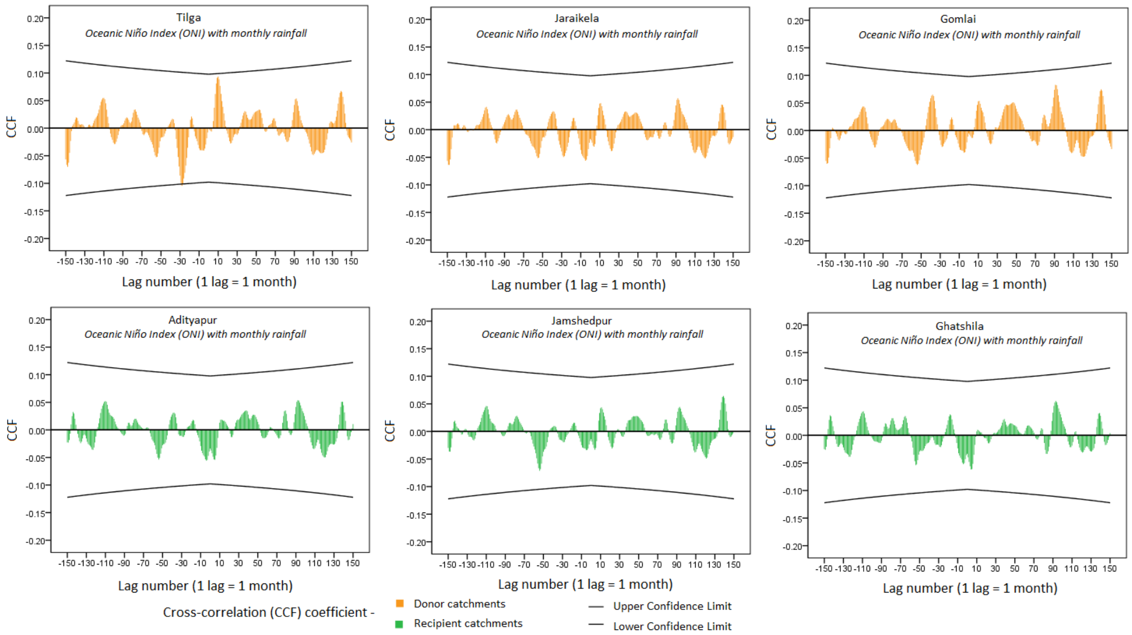


Figure 4.16: Cross-correlation of the Oceanic Nino Index (ONI) and monthly rainfall (1971-2005)

4.4.1.2 Seasonal and monthly rainfall

The water year runs from June to May with four distinct seasons (according to rainfall amounts) namely monsoon, post-monsoon, winter and pre-monsoon (Jain et al. 2007). In this thesis the water year is divided broadly into two seasons (Rao 1979): monsoon (June-September) and non-monsoon (October-May).

Most of the rainfall (80-86%) occurs in monsoon months (Table 4.8 & Table 4.9); thus, annual rainfall (Figure 4.12) closely follows rainfall in the monsoon season (Figure 4.17).

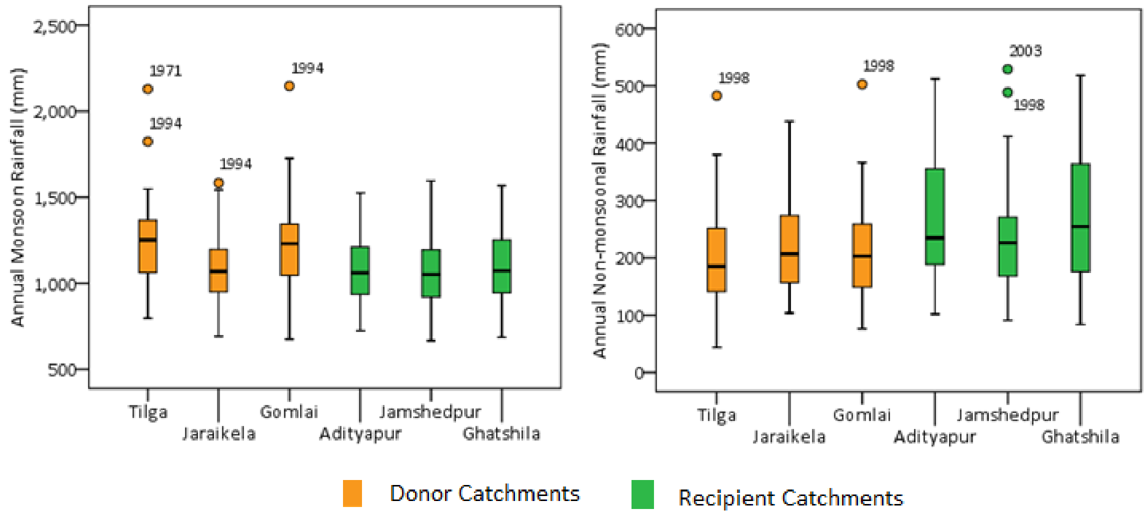


Figure 4.17: Box plot for the monsoon and non-monsoon rainfall per year during 1971-2005.

Monsoon rainfall increases westward (Figure 4.7) and so does its variability (Table 4.8). Donor catchments especially Tilga and Gomlai receive more monsoon rainfall than the other catchments (Table 4.8 & Table 4.9) and showed a similar spread in rainfall (Figure 4.17 and Table 4.8). The remaining four catchments showed a similar spread in monsoon rainfall. Influence of extreme events is visible in monsoon rainfall observed in the donor catchments (Figure 4.17). Median non-monsoon rainfall was higher in recipient catchments (Table 4.9); however, its large-spread indicates high variability (Figure 4.7, Figure 4.17). The non-monsoon rainfall clearly outlined the difference in donor and recipient catchments.

Table 4.8: Descriptive statistics of monsoon rainfall (mm) during 1971-2005.

Monsoon rainfall		Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean		1251	1092	1247	1067	1072	1099
Median		1251	1069	1230	1060	1051	1073
Standard deviation		260	199	272	191	207	218
Coefficient of variation (%)		21	18	22	18	19	20
Range		1332	892	1472	801	929	881
Minimum		797	691	675	724	667	686
Maximum		2129	1583	2147	1525	1596	1566
Percentiles	10	973	855	995	812	836	779
	25	1052	941	1034	927	904	927
	50	1251	1069	1230	1060	1051	1073
	75	1384	1200	1347	1212	1198	1262
	90	1534	1368	1603	1321	1365	1403

Table 4.9: Descriptive statistics of non-monsoon rainfall (mm) during 1971-2005.

Non-monsoon rainfall		Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean		206	228	210	269	239	278
Median		185	207	203	235	226	254
Standard deviation		100	88	91	113	100	118
Coefficient of variation (%)		48	38	43	42	42	43
Range		439	334	427	411	438	434
Minimum		44	104	76	102	91	84
Maximum		483	438	503	512	529	518
Percentiles	10	89	116	100	122	142	123
	25	141	154	138	185	168	172
	50	185	207	203	235	226	254
	75	269	275	269	355	281	382
	90	354	367	317	421	394	444

Both monsoon and non-monsoon rainfalls are significantly correlated in all catchments; correlation in the non-monsoon season is significantly stronger (Table 4.10 & Table 4.11). The catchments showed grouping as donor and recipient through their correlation co-efficient during both seasons.

Table 4.10: Correlation (Pearson Correlation) of monsoon rainfall in the catchments

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.805**	1				
Gomlai	.703**	.801**	1			
Adityapur	.510**	.764**	.760**	1		
Jamshedpur	.626**	.819**	.727**	.882**	1	
Ghatshila	.566**	.709**	.679**	.902**	.863**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.11: Correlation (Pearson Correlation) of non-monsoon rainfall in the catchments

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.914**	1				
Gomlai	.912**	.871**	1			
Adityapur	.822**	.913**	.820**	1		
Jamshedpur	.779**	.882**	.712**	.819**	1	
Ghatshila	.803**	.880**	.773**	.956**	.816**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Similar to annual rainfall, the two seasonal rainfalls were examined for both shorter and longer-duration cycles of wet-dry years. Autocorrelation of monsoon rainfall (Figure 4.18) was similar to that of annual rainfall and outlined cycles but largely insignificant, except in two cases (Figure 4.15). Tilga and Jaraikela showed statistically significant long-term cycles in the monsoon season. In the non-monsoon season, all catchments showed significant long-term cycles while only the recipient catchment showed significant short-term cycles (Figure 4.19).

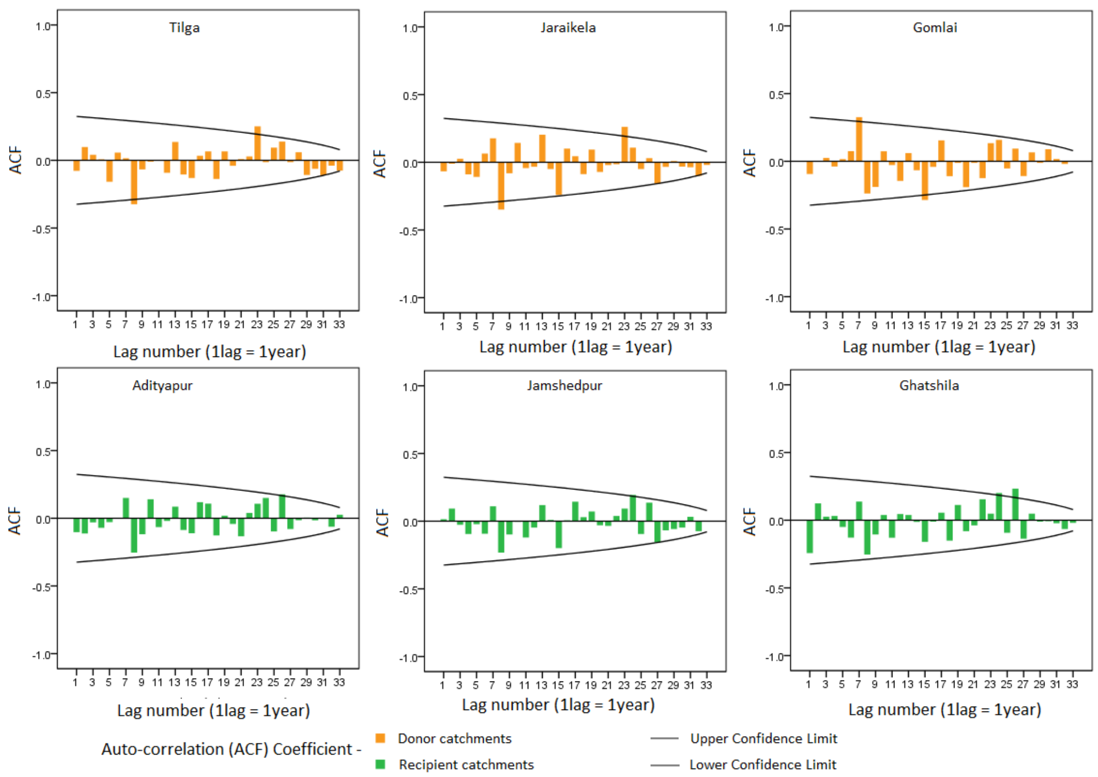


Figure 4.18: Auto-correlation (ACF) of monsoon rainfall in catchments.

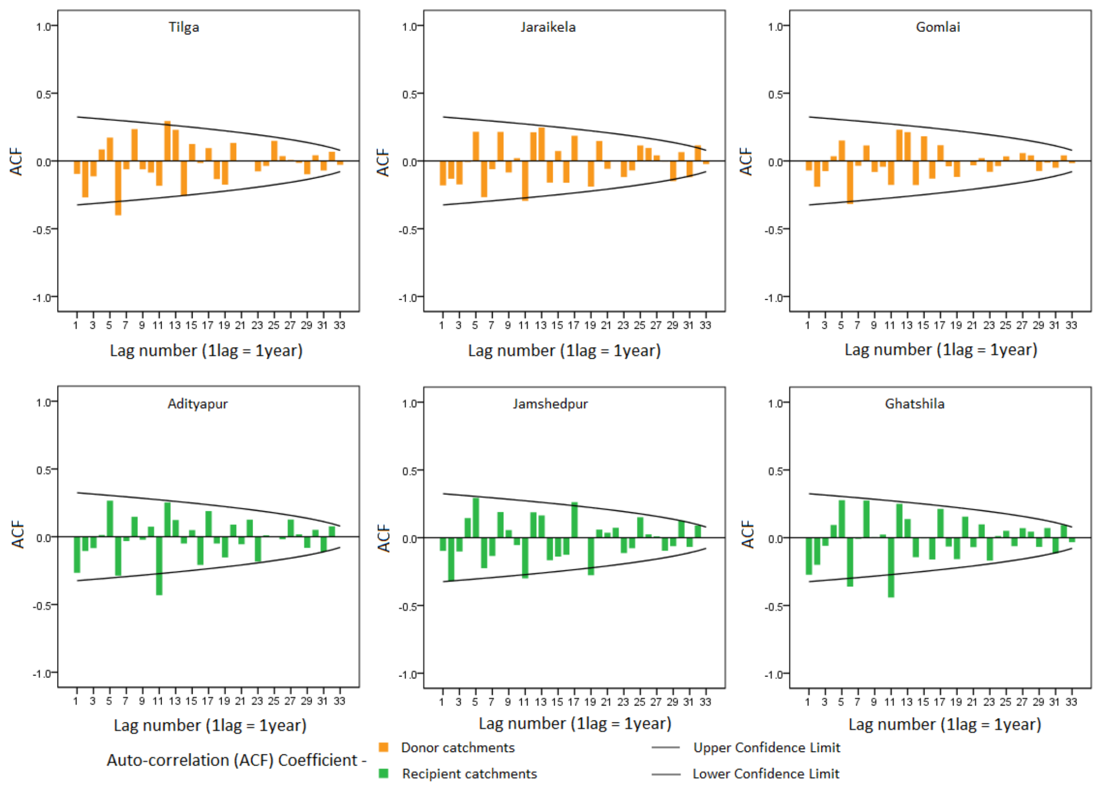


Figure 4.19: Auto-correlation (ACF) of non-monsoon rainfall in catchments.

Overall, all catchments showed similar monthly rainfall patterns during 1971-2005 (Figure 4.20). The catchments received around half of their rainfall in July and August (Figure 4.20). July is the wettest month in donor catchments while August is in recipient catchments. December is the driest month in all catchments with 0 mm monthly rainfall (Table 4.12) in most of the years.

Table 4.12: Descriptive statistics of monthly rainfall (mm) during 1971-2005.

Monthly rainfall	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean	122	110	121	111	109	115
Median	36.3	39.9	36.4	45.6	42.8	47.3
Standard deviation	158	135	160	130	131	134
Coefficient of variation (%)	130	123	132	117	120	117
Range	726	570	840	589	592	536
Minimum	0	0	0	0	0	0
Maximum	726	570	840	589	592	536

Donor catchments showed more variability in monthly rainfall than recipient catchments (Figure 4.20). Moving averages of two months' rainfall is least in Jaraikela among donor catchments and was only marginally higher than that of recipient catchments.

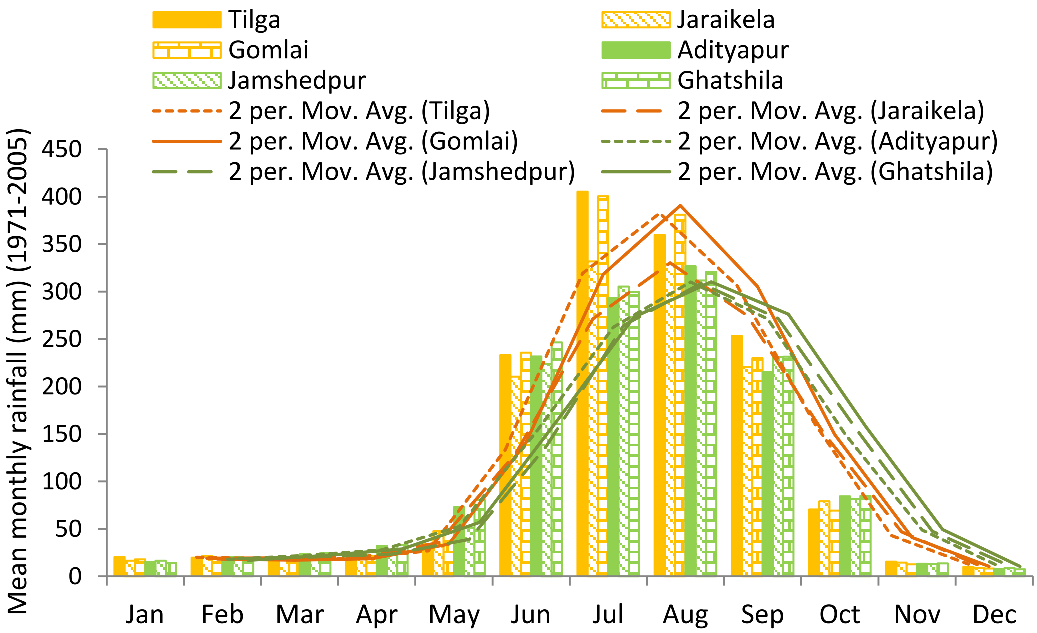


Figure 4.20: Mean monthly rainfall (mm) in the catchments during 1971-2005.

During 1971-2005, the monthly distribution of rainfall across catchments varied little; however, extreme monthly rainfalls were more common in the donor catchments than recipient catchments (Figure 4.21). It could influence the mean monthly rainfall and therefore could explain the higher mean rainfall in donor catchments (Table 4.12).

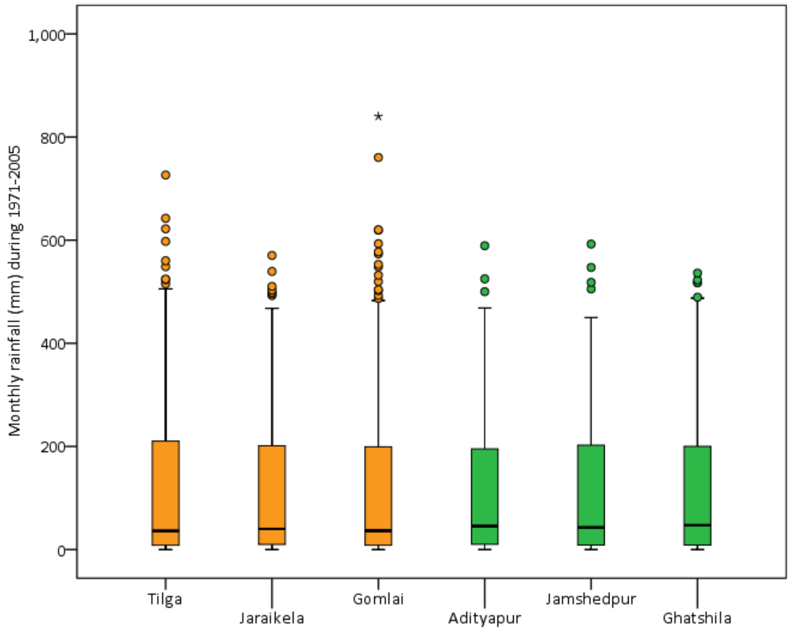


Figure 4.21: Box plot for monthly rainfall during 1971-2005.

Due to the seasonal spread, monthly rainfall was skewed in the catchments (Figure 4.21) showing that more months had lower monthly rainfall in them than their median monthly rainfall (Triola 1998). This trend is also evident in Figure 4.20. However, the magnitude of median monthly rainfall was slightly higher in the recipient catchments (Table 4.12) which could be due to greater non-monsoonal rainfall (Figure 4.17). However, as a percentage, contribution of non-monsoon rainfall is less in the total annual rainfall, therefore, the variation in median monthly rainfall of all catchments is negligible overall (Figure 4.21). Yet these non-monsoon rainfall quantities are important for water resource planning during the lean period. Overall, all of the catchments showed a similar spread and range of rainfall (Figure 4.21) and were highly correlated (Table 4.13).

Table 4.13: Correlation (Pearson Correlation) of monthly rainfall (mm) in the catchments

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.966**	1				
Gomlai	.960**	.971**	1			
Adityapur	.908**	.957**	.940**	1		
Jamshedpur	.933**	.967**	.936**	.965**	1	
Ghatshila	.905**	.938**	.921**	.980**	.963**	1
**. Correlation is significant at the 0.01 level (2-tailed).						

4.4.1.3 Trends in rainfall

The rainfall datasets based on the rainfall indices (Table 4.1) and the seasonal rainfall were first examined, for any abrupt or slow change, by the Pettitt test (Pettitt 1979). It showed no statistically significant change point in any of the rainfall datasets (Table 4.14).

Table 4.14: Sudden change points (year) in the annual rainfall (1971-2005) of the catchments (Pettitt test).

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean rainfall per year						
Year	1999	2000	1982	2001	1978	1978
Low rainfall indices						
Days with rainfall less than 2.5 mm						
Year	1999	1999	1982	1999	1998	1999
Days with rainfall <= mean rainfall						
Year	1999	1999	1982	1999	1999	1999
High rainfall indices						
Days with rainfall > 90th percentile						
Year	1999	2001	1999	1986	1985	1986
Maximum rainfall per year						
Year	1999	1993	1982	1978	1979	1978
Seasonal rainfall						
Mean monsoon rainfall						
Year	1999	1978	1982	2001	1997	2001
Mean non-monsoon rainfall						
Year	1986	1986	1979	1996	1986	1983
* Significant at the 0.05 level (2-tailed).						

Further, these datasets were assessed for any gradual change. Before performing non-parametric tests, Mann-Kendall *tau* and Spearman's *rho,* the rainfall datasets were examined for the serial autocorrelation effect (von Storch & Navarra 1995). As with Gocic & Trajkovic (2013), most of the rainfall datasets were found eligible and could be used directly as their r_1 was not significant at the 5% level (Gocic & Trajkovic 2013). Only four out of forty-two rainfall time-series were pre-whitened by subtracting their r_1 (significant at 5% level) from the original series (Wang & Vrijling 2005). Mann-Kendall *tau* and Spearman's *rho* tests were then carried out on all of datasets (Table 4.15).

Table 4.15: Gradual trends in the annual rainfalls (1971-2005) of the catchments (Mann-Kendall tau and Spearman's rho).

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean rainfall per year						
tau	-0.042	-0.202	0.069	-0.094	-0.184	-0.123
rho	-0.1	-0.257	0.093	-0.13	-0.244	-0.167
Low rainfall indices						
Days with rainfall less than 2.5 mm						
tau	0.082	0.114	-0.041	0.095	0.068	0.063
rho	0.114	0.134	-0.069	0.113	0.095	0.09
Days with rainfall <= mean rainfall						
tau	0.129	0.131	-0.003	0.075	0.017	0.068
rho	0.164	0.167	-0.028	0.095	0.04	0.09
High rainfall indices						
Days with rainfall > 90th percentile						
tau	-0.079	-0.147	-0.069	-0.19	-0.189	-0.105
rho	-0.115	-0.213	-0.113	-0.257	-0.249	-0.16
Maximum rainfall per year						
tau	0.029	0.018	0.082	-0.106	-0.166	-0.072
rho	0.019	0.039	0.121	-0.161	-0.234	-0.082
Seasonal rainfall						
Mean monsoon rainfall						
tau	-0.099	-0.193	0.045	-0.099	-0.17	-0.103
rho	-0.166	-0.277	0.054	-0.127	-0.243	-0.145
Mean non- monsoon rainfall						
tau	-0.092	-0.079	0.055	0.015	-0.099	-0.035
rho	-0.134	-0.112	0.079	0.008	-0.118	-0.042
* Significant at the 0.05 level (2-tailed).						

The two tests (Mann-Kendall *tau* and Spearman's *rho*) determined increasing and decreasing trends; however they were all statistically insignificant. Assessment for any abrupt change in mean monsoon and non-monsoon rainfall determined no statistically significant changing point (i.e. year) (Table 4.14). Further, the two non-parametric tests for gradual change, Mann-Kendall's *tau* and Spearman's *rho*, determined no significant change in either monsoon or non-monsoon seasons (Table 4.15).

4.4.2 Flow analysis

Before results of the flow analysis are presented, it should be noted that the Gomlai and Ghatshila catchments represent cumulative flow of donor and recipient basins respectively (Figure 4.1). Further, Ghatshila HOC is in close proximity (approximately 42 km^2) to the Jamshedpur HOC, with no other major inflow (Figure 4.1) or any major change in physical settings (section 4.3); therefore, their observed flows are similar.

4.4.2.1 Annual flow

The annual daily mean flow for the six catchments (1980-2013) is presented in Figure 4.22 and Table 4.16. As Gomlai and Ghatshila represent the flow of the entire donor and recipient basins respectively (Figure 4.1), they can be compared to assess the flow at basin scale (Table 4.16 and Figure 4.22). Gomlai showed higher mean annual flow than Ghatshila. As Jamshedpur is in close proximity to Ghatshila, the spread and range of the mean flows of Jamshedpur is similar to that of Ghatshila; and only exceeds marginally and is slightly more variable than flow at Ghatshila. Among upstream catchments of the donor and recipient basins, the annual flow range of Jaraikela, the main donor catchment, showed relatively higher flow than that of Adityapur, the main recipient catchment, at all flow dependability. Tilga showed the least range and spread of flow (Table 4.16). Flow variation displayed a similar pattern in the donor and recipient basins (Table 4.16). The skewness of annual mean flow for all catchments, except Gomlai is between -0.5 to +0.5 which indicates their nearly symmetrical distribution (GraphPad 2016).

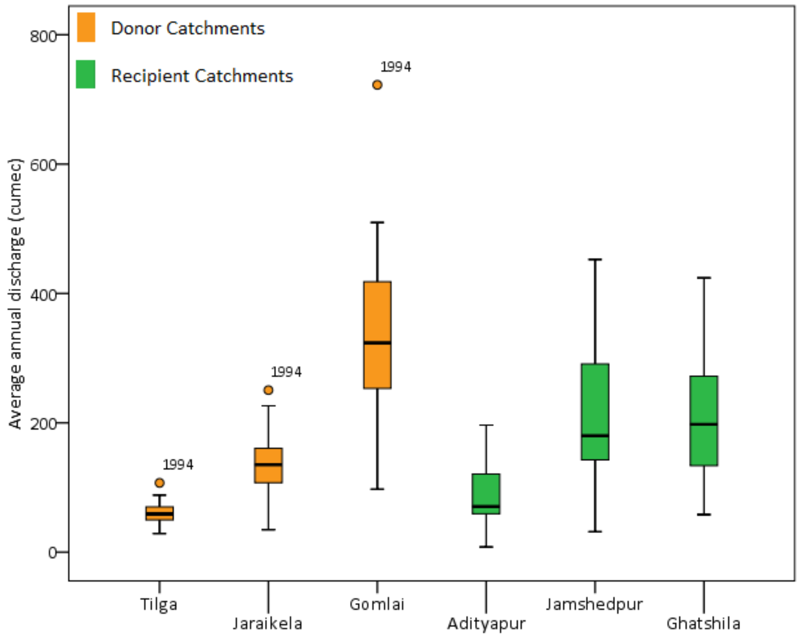


Figure 4.22: Box plot of annual flow (cumec) in catchments (1980-2013).

Table 4.16: Descriptive statistics of annual flow (cumec) in catchments under study.

Annual mean discharge (cumec)		Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Total years		34	34	34	34	34	34
Mean		61.8	138.3	345.4	90.1	215.0	215.2
Median		59.3	136.1	332.1	75.6	182.1	204.9
Standard deviation		17.2	48.5	121.6	42.7	99.9	96.5
Coefficient of variation (%)		27.8	35.1	35.2	47.4	46.5	44.9
Range		78.3	215.9	625.0	188.4	420.8	365.9
Minimum		28.8	34.6	97.5	8.1	31.7	58.2
Maximum		107.1	250.5	722.5	196.5	452.5	424.1
Skewness		0.42	0.23	0.71	0.51	0.47	0.52
Kurtosis (excess)		0.24	-0.01	1.56	-0.33	-0.43	-0.53
Percentiles	10	38.7	75.8	209.4	45.0	97.4	101.5
	25	50.0	106.8	256.2	59.5	143.8	134.1
	50	59.3	136.1	332.1	75.6	182.1	204.9
	75	72.8	165.3	422.8	122.1	291.7	286.2
	90	84.7	210.0	501.9	151.1	368.7	358.3

Positive Kurtosis (excess) in Tilga and Gomlai showed heavier tails in their flow datasets, indicating the influence of extreme events (McNeese 2016), corroborated by Figure 4.23. Negative Kurtosis (excess) but near to 0, shows a similar pattern for Jaraikela and explains the position of extreme events as seen in Figure 4.23

Furthermore, Tilga showed the highest while Jaraikela showed the lowest water yield (Figure 4.23). The water yield in donor catchments varied significantly which was contrary to the pattern seen in the recipient catchments (Figure 4.23).

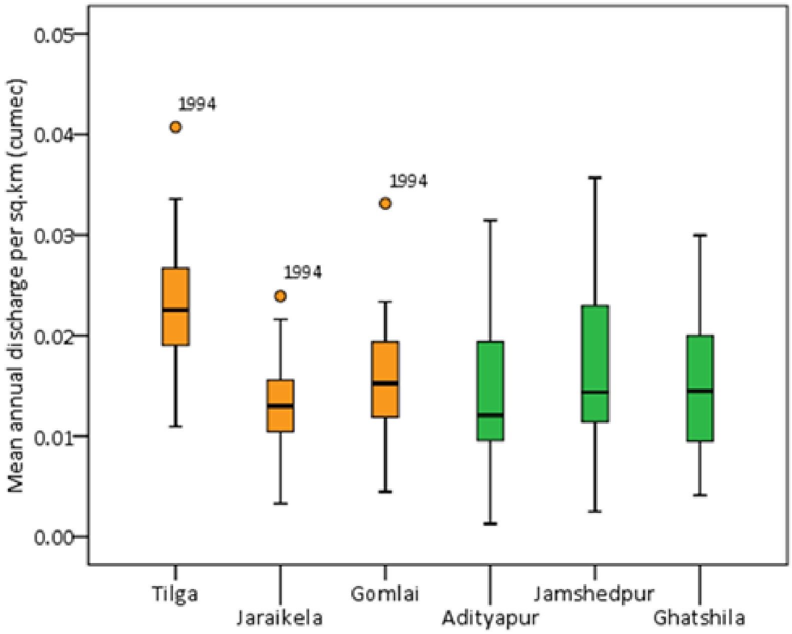


Figure 4.23: Box plot of water yield per year in the catchments (1980-2013).

Further, significant correlation was seen among catchments however donor and recipient basin-wise patterns are also evident (Table 4.17).

Table 4.17: Correlation (Pearson Correlation) of annual mean flow in the catchments (1980-2013).

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.725**	1				
Gomlai	.802**	.868**	1			
Adityapur	.530**	.711**	.821**	1		
Jamshedpur	.633**	.823**	.822**	.908**	1	
Ghatshila	.573**	.661**	.797**	.862**	.857**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 4.24 shows that annual mean flow and a moving average of five years for all catchments during 1972-2013. For two catchments, Tilga (1980-2013) and Jaraikela (1979-2013), data is for a reduced period. All catchments exhibited similar flow patterns of wet-dry years overall, but with minor variation between donor and recipient basins.

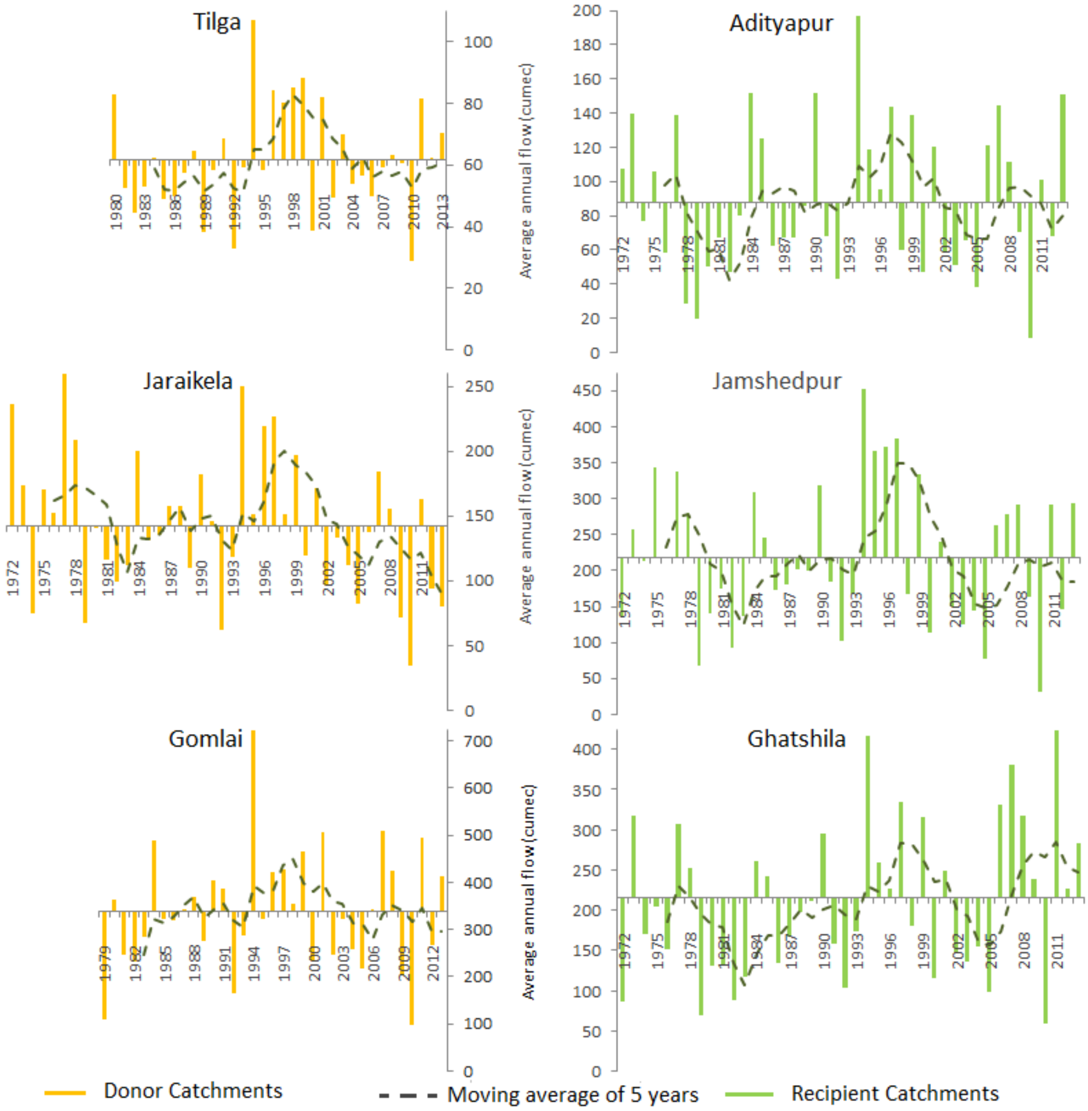


Figure 4.24: Pattern of annual flow along the long-term mean annual flow (cumec).

Similar to rainfall, annual daily mean flow also showed alternate wet and dry cycles over a few years in all catchments. Shorter wet and dry cycles were evident for 1-4 years. Longer duration cycles of 9-13 years were also evident (1979, 1989-90, 1999-2000) for significantly drier years in all catchments (Figure 4.25).

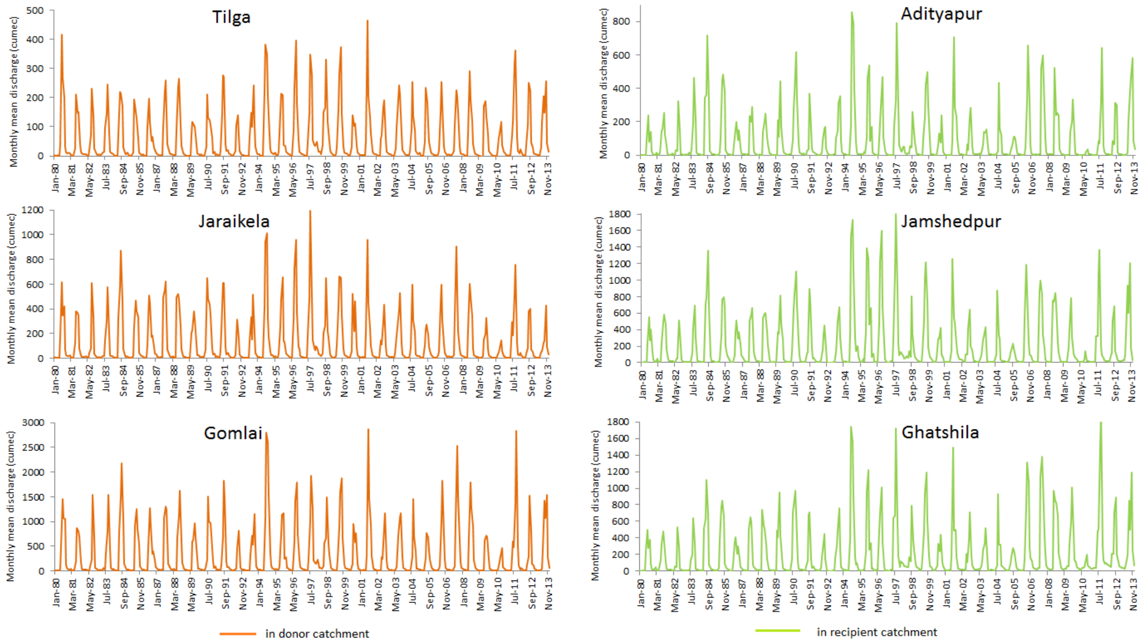


Figure 4.25: Monthly flow (cumec) in all catchments during June 1979 to December 2013.

The autocorrelations of annual flow also demonstrated both wet-dry years cycles (Figure 4.26). However, shorter duration cycles are statistically insignificant in all catchments except Adityapur. Longer duration cycles are statistically significant in Tilga, Adityapur and Jamshedpur; however they were not significant in Jaraikela, Gomlai and Ghatshila. Further, similar to rainfall, the influence of El Niño was noted by significant negative correlation between flow and ONI with a lag of 6-7 months between them in all catchments (Figure 4.27).

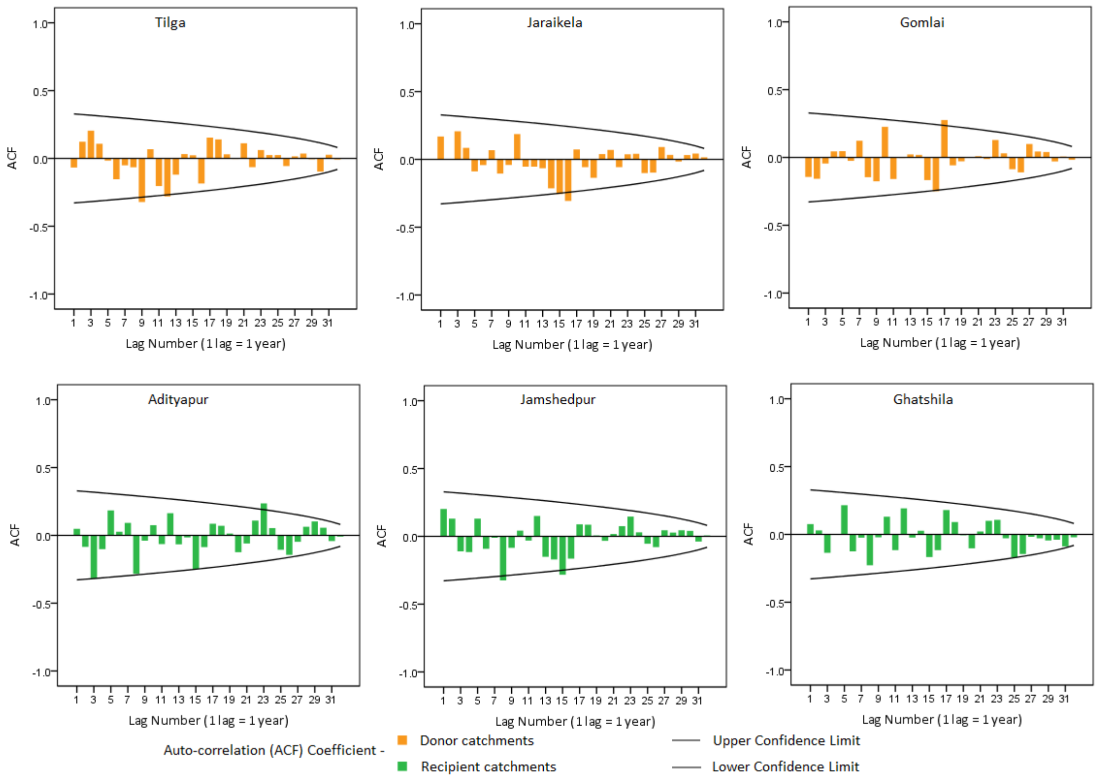


Figure 4.26: Auto-correlation of annual flow in catchments under study (1980-2013)

Figure 4.27: Cross-correlation of Oceanic Niño Index (ONI) with three-month moving mean monthly flow (1979-2013).

4.4.2.2 Seasonal and monthly flow

Similar to rainfall, annual flow is largely dominated by monsoon flow; thus, their patterns were similar (Figure 4.22 and Figure 4.28). However, patterns of non-monsoon flow differed from that of annual flow (Table 4.16 and Table 4.18).

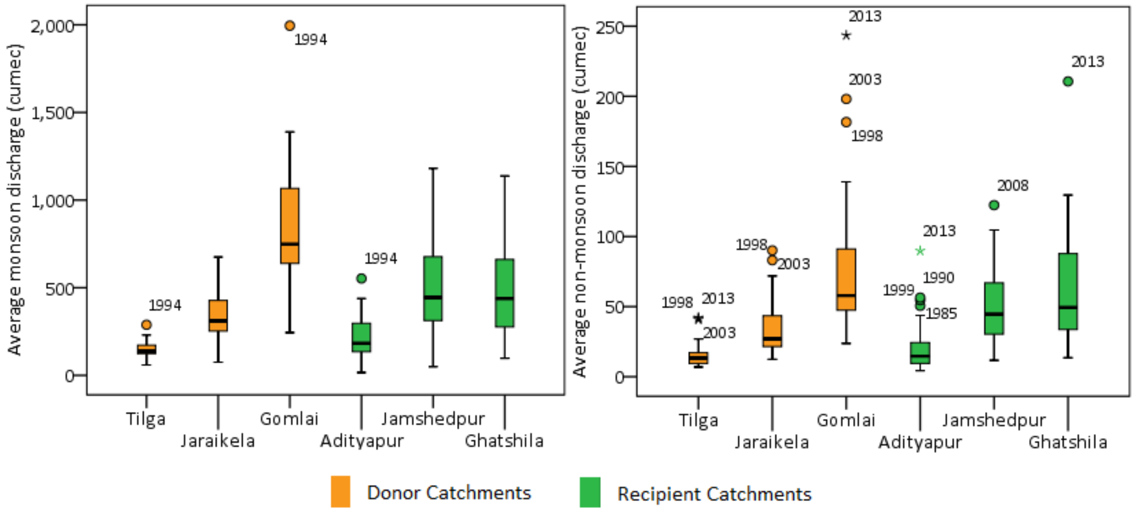


Figure 4.28: Box plot of annual monsoon and non-monsoon flow (1980-2013) (in cumec)

Table 4.18: Descriptive statistics of monsoon flow of all catchment (1980-2013).

Monsoon mean discharge (cumec)		Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean		152	342	873	226	507	512
Median		138	312	757	187	455	467
Standard deviation		47	140	346	117	267	265
Coefficient of variation (%)		31	41	40	52	53	52
Range		223	600	1751	537	1131	1041
Minimum		65.8	74.5	244.1	15.8	49.8	97.2
Maximum		288.5	674.5	1995	552.7	1180.5	1138.0
Percentiles	10	97.8	168.0	521.0	93.1	215.5	214.7
	25	124.1	254.5	639.1	137.0	312.9	279.1
	50	138.4	312.0	756.8	187.4	454.7	467.3
	75	174.3	436.5	1117.4	314.1	691.0	674.9
	90	220.8	576.0	1349.1	394.7	939.7	907.0

The mean monsoon flow leaving the donor basin (i.e. Gomlai) was significantly higher than that leaving the recipient basin (i.e. Ghatshila) (Table 4.18). Tilga, Gomlai and Adityapur showed influence of extreme events. However, the mean non-monsoon flow leaving Gomlai was only slightly higher than that of Ghatshila (Table 4.19). All catchments showed the influence of extreme events during the non-monsoon season (Figure 4.28). The monsoon flow is less variable than the non-monsoon flow (Table 4.18-Table 4.19). Recipient catchments showed higher variability in monsoon flow; however only Adityapur showed considerably higher variability in non-monsoon flow. The main donor catchments Jaraikela and Tilga performed better than the main recipient catchment Adityapur at all flow dependability.

Table 4.19: Descriptive statistics of non-monsoon flow of all catchment (1980-2013).

Non-monsoon mean discharge (cumec)		Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean		16	35	78	21	52	65
Median		14	28	60	15	46	50
Standard deviation		9	20	50	19	27	42
Coefficient of variation (%)		58	58	64	89	53	64
Range		35.2	77.7	219.8	85.5	110.7	194.7
Minimum		6.9	12.4	23.7	4.3	11.7	15.9
Maximum		42.1	90.1	243.5	89.8	122.4	210.6
Percentiles	10	8.2	15.7	30.7	5.9	17.1	22.6
	25	9.5	21.2	46.7	9.8	30.8	34.3
	50	13.5	27.6	60.2	14.8	45.7	49.7
	75	17.6	45.9	94.3	29.3	68.2	93.5
	90	33.8	69.2	160.3	52.6	95.5	117.7

However, mean seasonal water yield for the catchment showed different results. Like annual water yield, mean monsoon and non-monsoon water yield showed higher variability in the donor catchments (Figure 4.29). Jaraikela showed the least water yield in both seasons. Further, Tilga and Gomlai showed the influence of extreme events on monsoonal water yield. However, all catchments showed this influence in their non-monsoonal water yield.

Mean monsoon flows are significantly correlated (Table 4.20). Similar to the annual flow, they can be grouped as donor and recipient catchments. Mean non-monsoon flow showed highly significant correlation in all the catchments except for the catchment of Jamshedpur (Table 4.21). Jamshedpur showed no correlation with any of the other catchments, which could be attributed to the extensive irrigation in it (Figure 4.44).

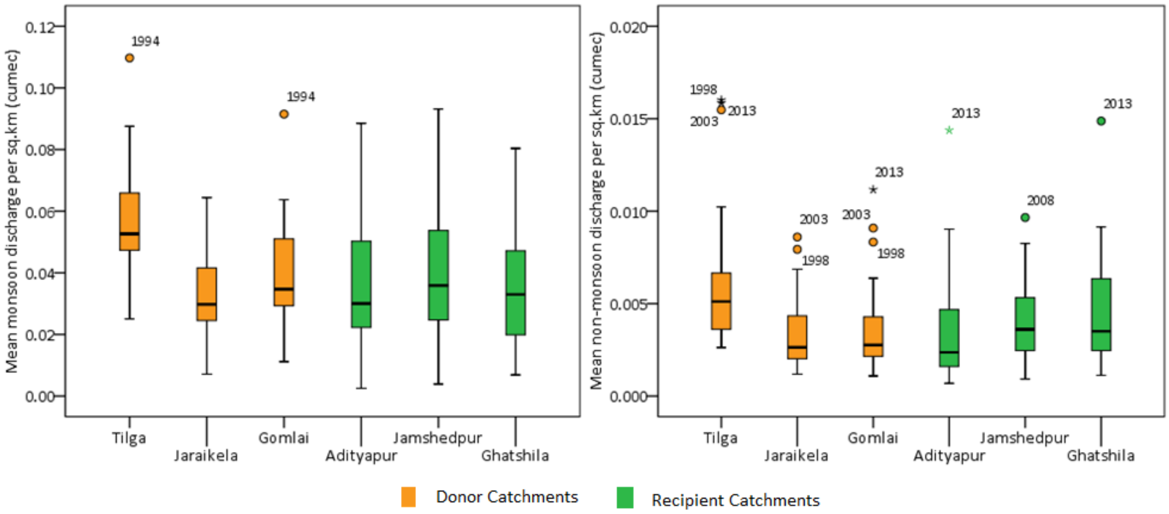


Figure 4.29: Box plot for monsoon and non-monsoon water yield (1980-2013)

Table 4.20: Correlation (Pearson Correlation) of monsoon mean flow in the catchments (1980-2013).

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.790**	1				
Gomlai	.840**	.892**	1			
Adityapur	.577**	.762**	.847**	1		
Jamshedpur	.705**	.870**	.852**	.914**	1	
Ghatshila	.636**	.755**	.840**	.899**	.897**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.21: Correlation (Pearson Correlation) of non-monsoon mean flow in the catchments (1980-2013).

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.906**	1				
Gomlai	.945**	.937**	1			
Adityapur	.724**	.784**	.836**	1		
Jamshedpur	0.094	0.182	0.176	0.142	1	
Ghatshila	.786**	.761**	.840**	.843**	0.138	1

**. Correlation is significant at the 0.01 level (2-tailed).

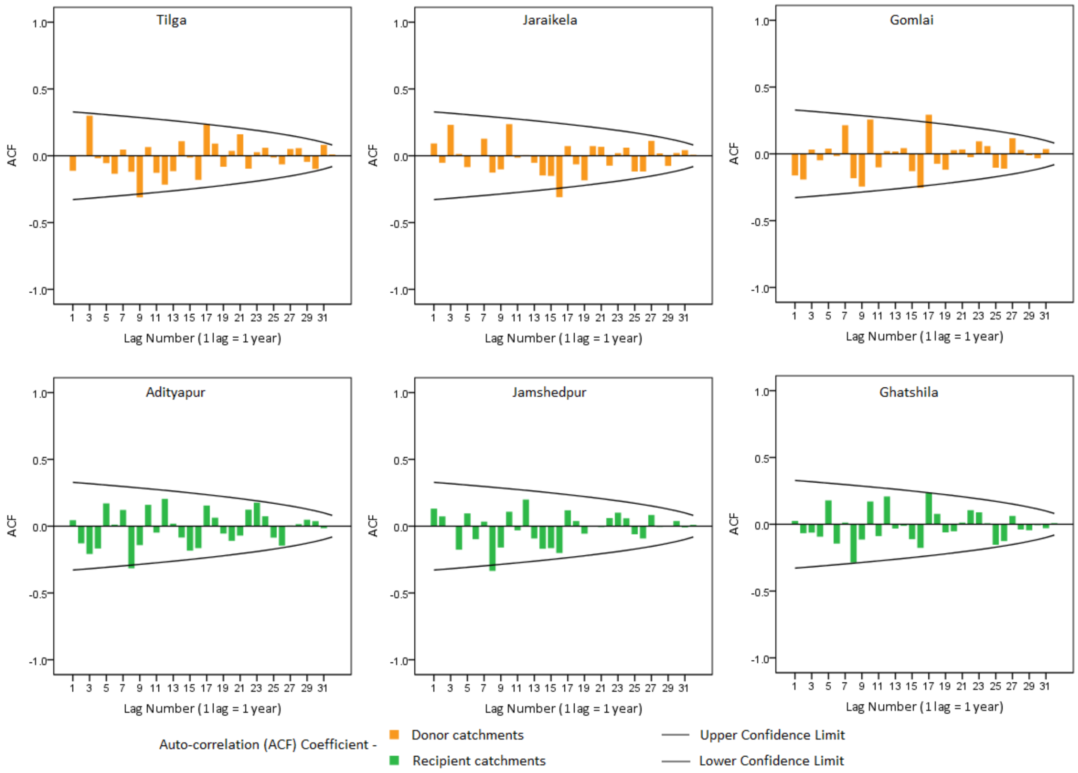


Figure 4.30: Auto-correlation of monsoon flow in catchments (1980-2013)

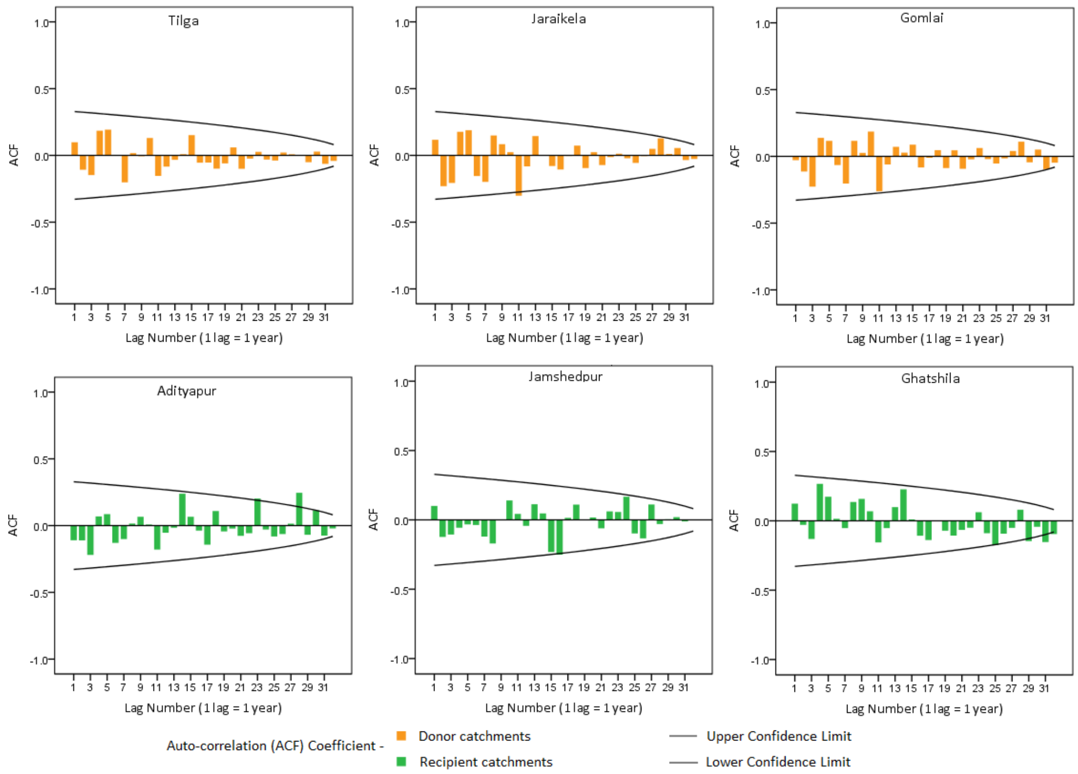


Figure 4.31: Auto-correlation of non-monsoon flow in catchments (1980-2013)

Autocorrelation of mean monsoon flow (Figure 4.30) was similar to that of annual flow (Figure 4.26) and outlined both shorter, as well as longer cycles, of wet and dry years. Shorter duration cycles are evident in mean monsoonal flow of all catchments; however they are statistically insignificant in all except Tilga. Longer duration cycles are statistically significant in Tilga, Adityapur, Jamshedpur and Ghatshila; however they are moderately significant in Gomlai and insignificant in Jaraikela. For mean non-monsoon flow, shorter duration wet-dry cycles are visible but statistically insignificant, while longer duration cycles are significant in Jaraikela and Gomlai (Figure 4.31).

Further, descriptive statistics of monthly flow for all catchments during 1980-2013 are given in Table 4.22. Minimum monthly flow in the study area reached 0 cumec (Tilga) while maximum monthly touched 2860 cumec (Gomlai). Similar to annual flows, Gomlai and Ghatshila showed a higher monthly flow (Table 4.22).

Table 4.22: Descriptive statistics of monthly flow in catchments during 1980-2013

Monthly mean discharge (cumec)	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Mean	61.3	137.4	343.1	89.6	213.8	214.1
Median	13.3	26.2	54.4	10.7	48.8	50.8
Standard deviation	88.7	208.7	534.7	153.8	331.9	332.2
Coefficient of variation (%)	145	152	156	172	155	155
Range	465	1190	2854	853	1806	1909
Minimum	0.0	1.4	5.4	0.3	0.4	1.5
Maximum	465	1192	2860	854	1806	1910

Similar to monthly rainfall, monthly flow is also largely dependent on the monsoon season (June-September) (Figure 4.32). Approximately one month's lag is noted in monthly flow compared to monthly rainfall (Figure 4.20), which could be attributed to rainfall-runoff processes due to the landscape characteristics of catchments. August and September showed higher monthly flow in all catchments, while April-May showed lower monthly flow (Figure 4.32).

Gomlai demonstrated the highest monthly flow and was followed by Ghatshila and Jamshedpur; Tilga has the lowest monthly flow but when compared to water yield, it ranked first (Figure 4.32a&b). The rest of the catchments showed similar water yields. Jaraikela showed the lowest monthly water yield during August-December while Adityapur showed the lowest in the remaining months. Moving averages of two months' flow indicated that Jaraikela largely had the least mean monthly water yields among the donor catchments.

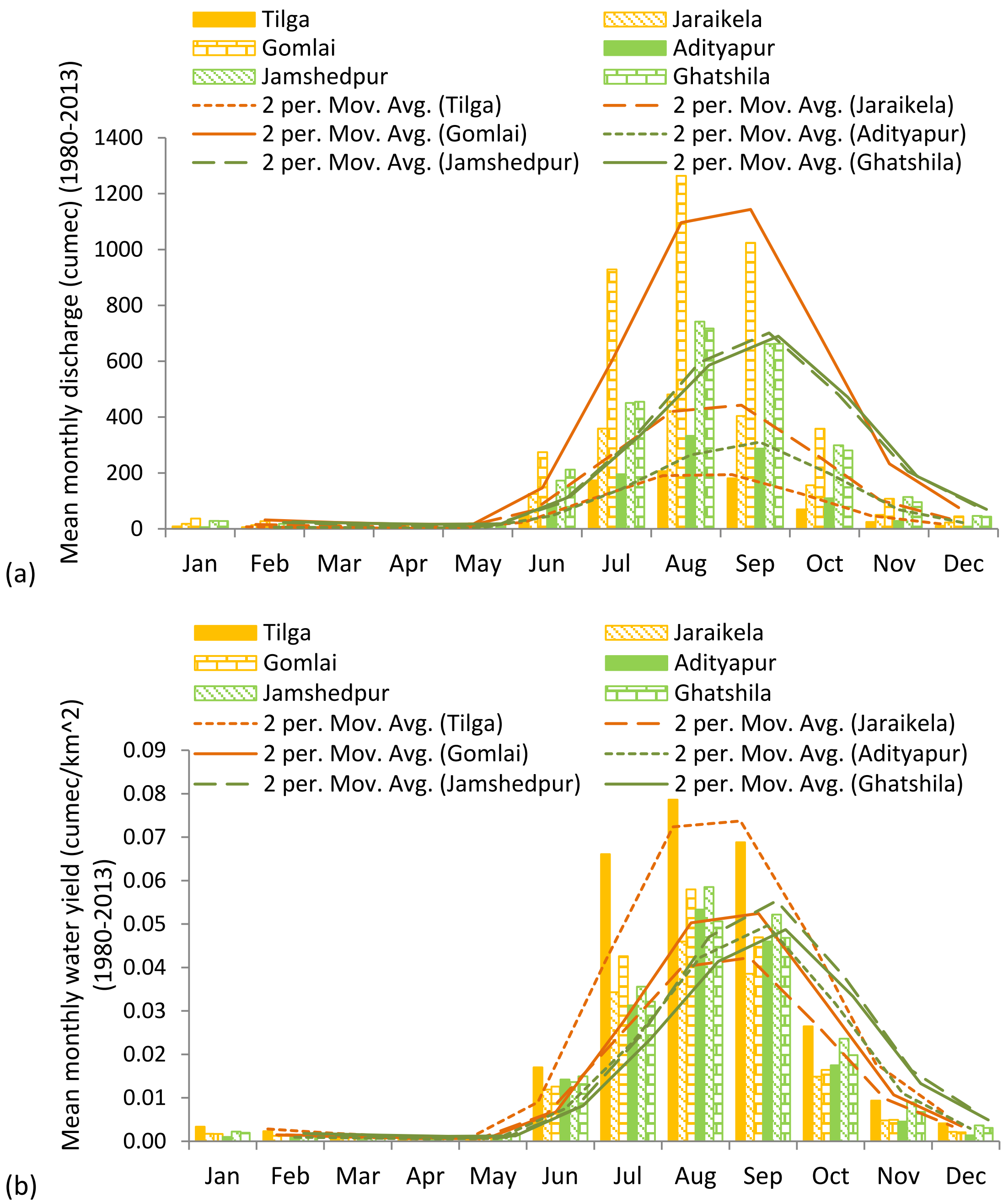


Figure 4.32: (a) Monthly flow (cumec) in the catchments (b) Monthly water yield in the catchments.

Range and spread in monthly flow, along with the influence of extreme monthly flow, are highest in Gomlai and then in Ghatshila and Jamshedpur (Figure 4.33).

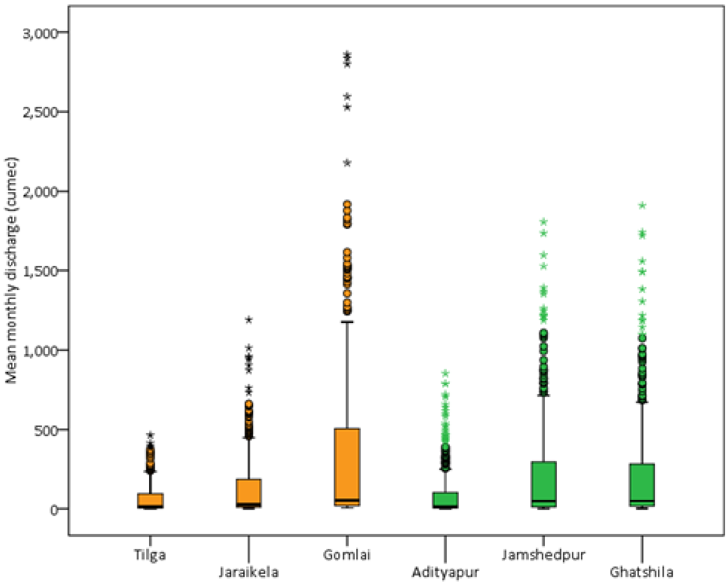


Figure 4.33: Box-plot of monthly flow (cumec) in the catchments(1980-2013).

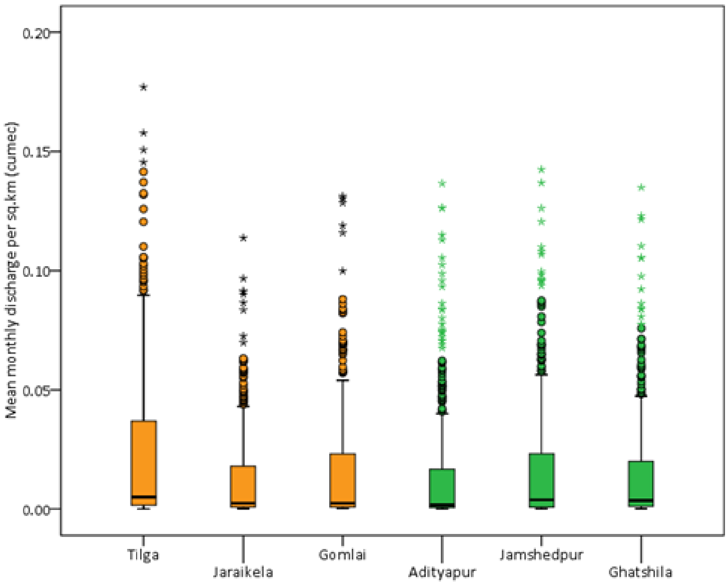


Figure 4.34: Box-plot of monthly water yield (cumec/km^2) in the catchments (1980-2013).

Figure 4.34 also showed that Jaraikela has the least monthly water yield and was closely followed by Adityapur. Tilga has the highest monthly water yield among all catchments, but with the maximum inter-quartile range indicating greater variability. The rest of the catchments showed similar monthly water yields.

Further, as with annual flow, monthly flow of all catchments showed significant correlation (Table 4.23).

Table 4.23: Correlation (Pearson Correlation) of monthly flow during 1980-2013.

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Tilga	1					
Jaraikela	.930**	1				
Gomlai	.951**	.960**	1			
Adityapur	.826**	.893**	.910**	1		
Jamshedpur	.860**	.921**	.912**	.955**	1	
Ghatshila	.851**	.903**	.915**	.956**	.958**	1

**. Correlation is significant at the 0.01 level (2-tailed).

4.4.2.3 Trends in flow

The flow datasets based on flow indices (Table 4.1) and seasonal flow were examined for sudden (Pettitt test) or gradual change (Mann-Kendall *tau* and Spearman's *rho*). Table 4.24 shows sudden change points while Table 4.25 shows gradual trends observed in the flow datasets. Table 4.26 represents the simplified version of these flow trends (Table 4.24 and Table 4.25) exhibiting increasing (+) or decreasing (-) trends showing statistically significant trend in 'bold'. 4. Also, Table 4.26 shows only those sub-series level trend analyses which have significant sudden change points.

These sudden and gradual changes, given in Table 4.24 and Table 4.25 with simplified version of these flow trends given in Table 4.26, are used to describe the trends in the flow of each catchment.

Donor catchments

Tilga showed no significant trend in mean, low flow indices, high flow indices, flow at 75% dependability, days with flow less than 75% dependability or mean monsoon flow. Insignificant *tau* but significant *rho* indicated a slightly positive trend for non-monsoon flow in Tilga, which showed a significant change point (1992) through the Pettitt test. It led to a sub-series level trend analysis for the period before and after 1992 which revealed respectively insignificant positive and negative trends in them. Overall, no flow trend was significant in Tilga.

Table 4.24: Sudden change points (year) in the annual flow (1980-2013) of the catchments (Pettitt test)

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
						Annual Flow
Mean flow per year						
Year	1993	2001	1993	1982	1999	1993
Low flow indices						
Minimum flow per year						
Year	2010	1989	2000	1997**	1997**	1997**
Per year flow less than 1 percentile						
Year	2010	1989	1999*	1997**	1997**	1997**
Number of days with flow less than 1 percentile						
Year	1998	2009	2004	1982*	1997*	1997**
Per year flow less than 10 percentile						
Year	1994	2008	2000*	2002*	1997**	1997**
Number of days with flow less than 10 percentile						
Year	1994	2008	2000*	1997**	1997**	1997**
Important for two ILR links under study						
Per year flow with 75% dependability (i.e. flow < 25 percentile)						
Year	1994	2008	2000*	1983	1996**	1996**
Number of days with 75% dependable flow						
Year	1994	2008	2000*	2008	1996**	1996**
High flow indices						
Maximum flow per year						
Year	1993	2007	1986	1993	1993	1983
Per year flow greater than 90 percentile						
Year	1993	2001	1999	1982	1997	2005
Number of days with flow greater than 90 percentile						
Year	1993	1999	2001	1982	1999	2005
Per year flow greater than 95 percentile						
Year	1992	2001	2001	1992	1983	1993
Number of days with flow greater than 95 percentile						
Year	1992	2001	2010	1982	1993	1993
						Seasonal flow
Mean monsoon flow per year						
Year	1992	2001	2001	2005	1997	1983
Mean non-monsoon flow per year						
Year	1992*	1984	1984	1984	1999	1997*

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.25: Gradual trends in the annual flows (1980-2013) of the catchments (Mann-Kendall *tau* and Spearman's *rho*)

	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
						Annual Flow
Mean flow per year						
tau	0.134	-0.116	0.048	0.055	0.02	0.223
rho	0.169	-0.18	0.042	0.069	0.016	0.326
Low flow indices						
Minimum flow per year						
tau	0.06	0.03	-0.048	.584**	.514**	.510**
rho	0.083	0.066	-0.101	.770**	.740**	.661**
Per year flow less than 1 percentile						
tau	0.048	-0.02	-0.173	.547**	.533**	.533**
rho	0.08	0.011	-0.248	.725**	.757**	.713**
Number of days with flow less than 1 percentile						
tau	0.092	0.056	0.071	-.376**	-.303*	-.354**
rho	0.121	0.041	0.089	-.453**	-.390*	-.495**
Per year flow less than 10 percentile						
tau	0.174	-0.02	-0.199	.255*	.501**	.526**
rho	0.237	0.008	-0.289	.393*	.705**	.727**
Number of days with flow less than 10 percentile						
tau	-0.186	0.052	0.213	-.394**	-.542**	-.528**
rho	-0.296	0.06	0.295	-.545**	-.752**	-.717**
Important for two ILR links under study						
Per year flow with 75% dependability (i.e. flow < 25 percentile)						
tau	0.073	-0.055	-0.18	0.073	.326**	.494**
rho	0.12	-0.09	-0.264	0.1	.496**	.682**
Number of days with 75% dependable flow						
tau	-0.084	0.068	0.165	-0.123	-.349**	-.495**
rho	-0.144	0.106	0.258	-0.118	-.532**	-.673**
High flow indices						
Maximum flow per year						
tau	0.039	0.005	0.037	0.112	0.187	0.15
rho	0.081	-0.01	0.021	0.144	0.261	0.223
Per year flow greater than 90 percentile						
tau	0.012	-0.234	-0.02	0.07	-0.027	0.13
rho	0.045	-0.332	-0.053	0.105	-0.064	0.18
Number of days with flow greater than 90 percentile						
tau	0.018	-0.171	-0.034	0.081	0.03	0.158
rho	0.036	-0.238	-0.055	0.105	0.039	0.224
Per year flow greater than 95 percentile						
tau	0.127	-0.144	0.009	0.077	0.062	0.173
rho	0.189	-0.189	0.017	0.101	0.09	0.247

Number of days with flow greater than 95 percentile						
tau	0.104	-0.086	0.076	0.047	0.073	0.234
rho	0.153	-0.117	0.101	0.055	0.11	.345*
						Seasonal flow
Mean monsoon flow per year						
tau	0.005	-0.166	-0.045	0.037	0.016	0.134
rho	0.007	-0.237	-0.089	0.059	-0.006	0.171
Mean non-monsoon flow per year						
tau	0.234	0.102	0.105	0.048	-0.005	.394**
rho	.350*	0.158	0.153	0.064	0.007	.536**

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Jaraikela showed no significant change point. Similar to Tilga, Jaraikela showed insignificant trends in flow whether it is mean, low or high flow indices. Flow with 75% dependability in Jaraikela showed a decrease and the number of days with flow less than 75% dependability increased during 1980-2013; however, these trends were insignificant. Trends in seasonal flow are also insignificant.

Gomlai showed no significant change point or trend in mean, high and seasonal flow indices. Under low flow indices, minimum flow and flow less than 1 percentile showed an insignificant negative trend, while days with flow less than 1 percentile showed an insignificant positive trend. Flow under 1 percentile showed a significant change point (1999) leading to a sub-series trend analysis which demonstrated a significant positive trend before 1999 while an insignificant negative trend emerged after 1999. Flow at 10th and 25th percentile showed a significant change point (2000) and a negative trend (significant for the former and insignificant for the latter). Both flow indices showed significant positive trends before 2000 indicating an increase in the flow indices; however, they decreased insignificantly after 2000. Further, their number of days increased but the trend is significant only for the days with flow at the 10th percentile. Nevertheless, this indicated an increase in the number of days with low flows at 10th and 25th percentile. Further, days with flow at the 10th percentile also showed significant sudden change in 2000 leading to a sub-series trend analysis. The analysis indicated that the number of days with flow at the 10th percentile decreased significantly before 2000, but increased insignificantly after 2000. Thus, in general, low flow indices indicated a decreasing trend in Gomlai but when the sudden change point in 2000 is considered, these trends are insignificant.

Table 4.26: Simplified version of the flow trends in the catchment (1980-2013) based on the Table 4.24 and Table 4.25 exhibiting increasing (+) or decreasing trend (-).

(tau/rho)	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
						Annual flow
Mean flow	+/+	-/-	+/+	+/+	+/+	**+/+**
Low flow indices						
Min flow	+/+	+/+	-/-	**+/+ ***	**+/+ ***	**+/+ ***
Before period				**+/+**	-/-	+/+
After period				**+/+**	+/+	+/+
Per year flow < 1 percentile	+/+	-/+	-/- *	**+/+ ***	**+/+ ***	**+/+ ***
Before period			**+/+**	**+/+**	-/-	+/+
After period			-/-	**+/+**	**+/+**	+/+
Days with flow < 1 percentile	+/+	+/+	+/+	**-/- ***	**-/- ***	**-/- ***
Before period				-/-	-/-	-/-
After period				-/-	-/-	-/-
Per year flow < 10 percentile	+/+	-/+	**-/- ***	**+/+ ***	**+/+ ***	**+/+ ***
Before period			**+/+**	+/+	-/-	+/+
After period			-/-	-/-	+/-	**+/+**
Days with flow < 10 percentile	-/-	+/+	**+/+ ***	**-/- ***	**-/- ***	**-/- ***
Before period			**-/-**	-/-	+/+	-/-
After period			+/+	-/-	**-/-**	-/-
Important for two ILR links under study						
Flow with 75% dependability	+/+	-/-	-/- *	+/+	**+/+ ***	**+/+ ***
Before period			**+/+**		-/-	-/-
After period			-/-		-/-	+/+
Days with flow at 75% dependability	-/-	+/+	+/+	-/-	**-/- ***	**-/- ***
Before period					+/+	+/+
After period					-/-	**-/-**
High flow indices						
Maximum flow	+/+	+/-	+/+	+/+	+/+	+/+
Per year flow > 90 percentile	+/+	-/-	-/-	+/+	-/-	+/+
Days with flow > 90 percentile	+/+	-/-	-/-	+/+	+/+	+/+
Per year flow > 95 percentile	+/+	-/-	+/+	+/+	+/+	+/+
Days with flow > 95 percentile	+/+	-/-	+/+	+/+	+/+	+/+

						Seasonal flow
Mean monsoon flow	+/+	-/-	-/-	+/+	+/-	+/+
Mean non-monsoon flow	+/**+** *	+/+	+/+	+/+	+/+	**+/+ ***
Before period	+/+					+/+
After period	-/-					+/+

Note:

1. Trends (+ or -) are written as - Kendall's *tau*/Spearman's *rho*
2. Trends as 'bold' are significant (with p-value of 0.01 or 0.05 in most cases and in two cases it is 0.1). Details are given in Table 4.24 and Table 4.25.
3. Asterisk (*) represent a significant break point (with p-value of 0.01 or 0.05)
4. Only flow indices which have significant sudden change points show trends for before and after periods estimated through sub-series level trend analysis.

Recipient catchments

Adityapur showed positive trends for mean, high and seasonal flow; however the trends are statistically insignificant. Significant change points are observed in all five low flow indices with significant increases in the three low flows (minimum, 1 and 10th percentile) and a significant decrease in the number of days with low flows under the 1st and 10th percentile. It indicated that low flow conditions improved in Adityapur. The subseries trend analysis also affirmed this trend and indicated similar trends (mostly significant) for minimum flow and flow under 1 percentile before and after the change point. The flow indices related to the 10th percentile also showed similar, but insignificant trends before and after change points except for one. For the period after change point (2002), flow under the 10th percentile decreased, but this trend is statistically insignificant. Further, the flow important for the ILR links (75% dependable flow), increased while the number of days with flow less than 75% dependability decreased; both of these trends are insignificant. Nevertheless it indicated an improvement of 75% dependable flow in Adityapur.

Jamshedpur showed no significant trend in mean and high flow, although insignificant positive trends were observed in all of them except one (flow above 90th percentile). The flow above the 90th percentile showed an insignificant negative trend. A significant change point (1997) is observed in all five low flow indices with a significant increase in the three low flows (minimum, 1st and 10th percentile) and a significant decrease in the number of days with flows under the 1st and 10th percentile. This indicated an improvement in the low flow conditions of

Jamshedpur, however subseries trend analysis of these flows showed some different but mostly insignificant trends. The flow under the 1st percentile showed a significant positive trend after its change point (1997). Also, the number of days with flow under the 10th percentile showed a significant negative trend after its change point (1997). Further, flow important for ILR links (75% dependable flow) showed significant increase. Also, the number of days with flow less than 75% dependability decreased significantly. Both indices showed a significant sudden change in 1996, however, no significant trend is observed in their sub-series analysis. Nonetheless, it indicated improvement in the flow with 75% dependability at Jamshedpur. Seasonal flow showed insignificant trends but values were close to zero. Overall, except low flows, all flows showed insignificant trends in Jamshedpur. The low flows showed significant improvements in the catchment.

Ghatshila demonstrated a significant positive trend in the mean annual flow. It also showed positive trends in high flow indices, but they are mostly insignificant. Similar to Adityapur and Jamshedpur, Ghatshila also showed a significant sudden change point in 1997 for all five low flow indices, significant increase in the three low flows (minimum, 1 and 10th percentile) and a significant decrease in the number of days with flows under the 1st and 10th percentile. These trends indicated improvement in low flow conditions at Ghatshila. The subseries trend analysis of these flows demonstrated the same trends in all datasets before and after 1997; however, the trends are mostly insignificant except for flow under the 10th percentile after 1997. Similar to Jamshedpur, flow important for ILR links (75% dependable flow) showed an increase in Ghatshila, while the number of days with flow less than 75% dependability decreased; both trends are significant, indicating improvement in the flow. Further, both indices showed significant sudden change in 1996. The flow at 75% dependability showed a negative trend before 1996 and a positive trend after, but both trends were insignificant. These results were corroborated by the number of days with flow less than 75% dependability, which showed an insignificant positive trend before 1996, but a significant negative trend after 1996. Nevertheless, Ghatshila showed improvement in the flow with 75% dependability. Seasonal flow showed positive trends; however, it is insignificant for monsoon and significant for non-monsoon. Non-monsoon flow showed a significant sudden change point (1997). Sub-series analysis demonstrated a similar trend before and after 1997; however the trends are insignificant. Overall, Ghatshila showed improvements in low flow conditions.

4.4.3 Rainfall and flow

The relationship between annual rainfall and flow was examined by visual comparison of annual mean rainfall and flow with a five year moving average (Figure 4.13 and Figure 4.24). Similar patterns of wet-dry cycles were observed in both of them.

Further, both datasets showed significant correlation in each of the catchments, with maximum correlation in Gomlai (Table 4.27). Their correlation across years, when examined, was significant for the same year only (Figure 4.35). The runoff-rainfall ratio is highest in Tilga and lowest in Jaraikela.

Table 4.27: Relation between rainfall and flow (annual mean) during 1980-2005

Catchments	Correlation coefficient (Pearson) **Significant at 0.01 level (2-tailed)	Runoff-rainfall ratio
Tilga	0.746**	0.51
Jaraikela	0.787**	0.32
Gomlai	0.928**	0.35
Adityapur	0.805**	0.34
Jamshedpur	0.697**	0.40
Ghatshila	0.796**	0.36

The scatter-plots of mean annual rainfall and flow in all catchments showed a linear relationship (Figure 4.36).

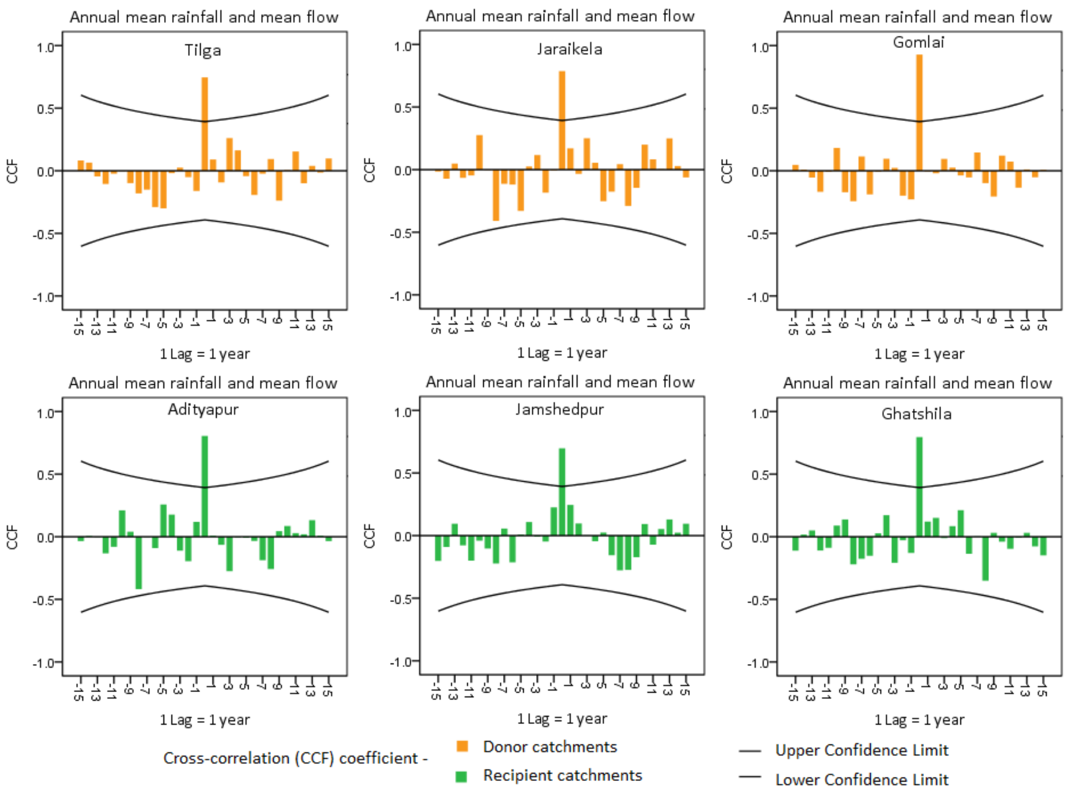


Figure 4.35: Cross-correlation of annual mean rainfall and flow of the catchments (1980-2005).

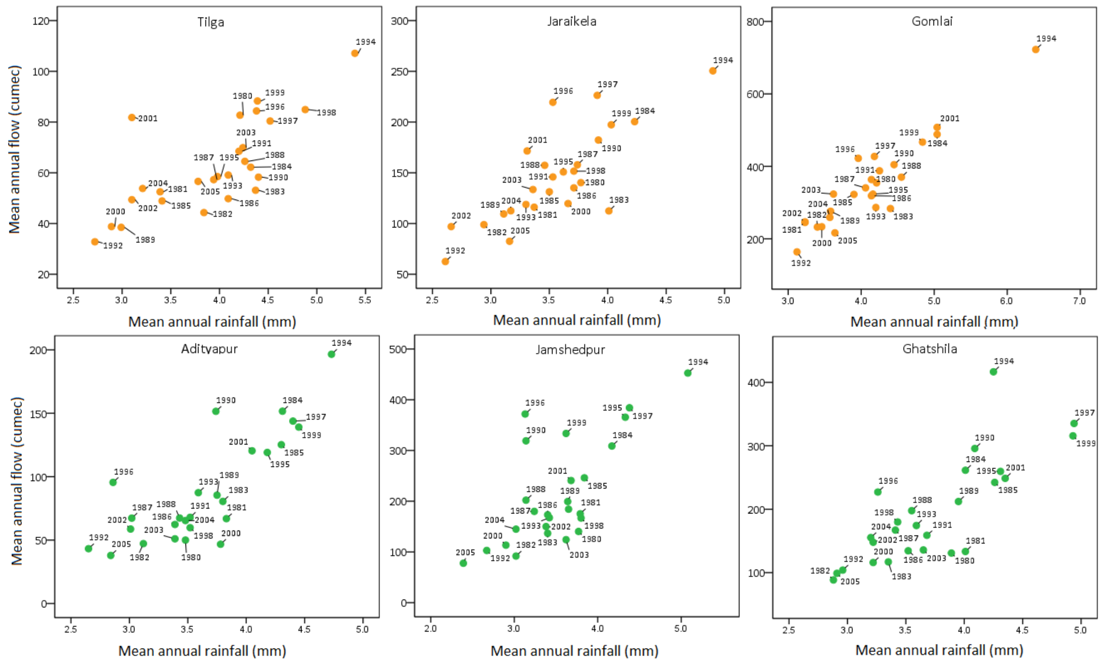


Figure 4.36: The scatter-plots of annual mean rainfall and flow of the catchments (1980-2005).

The relationships between seasonal rainfall and flow of all catchments were cross-correlated. In all catchments, monsoon rainfall showed significant correlation with monsoon flow of the same year (Table 4.28).

Table 4.28: Correlation of seasonal rainfall and flow during 1980-2005.

	Rainfall and flow		
Catchments	Monsoon rainfall and Monsoon flow	Non-monsoon rainfall and Non-monsoon flow	Monsoon rainfall and non-monsoon flow
Tilga	0.823**	0.699**	0.163
Jaraikela	0.854**	0.793**	-0.122
Gomlai	0.944**	0.723**	-0.108
Adityapur	0.860**	0.750**	-0.038
Jamshedpur	0.825**	0.101	0.603**
Ghatshila	0.856**	0.746**	-0.061

**. Correlation is significant at the 0.01 level (2-tailed).

In all catchments except Jamshedpur, non-monsoon rainfall showed significant correlation with non-monsoon flow of the same year. In Jamshedpur, non-monsoon rainfall showed a positive relationship, but it was not statistically significant with non-monsoon flow; however for the same year, its monsoonal rainfall showed a statistically significant relation with non-monsoonal flow (Table 4.28).

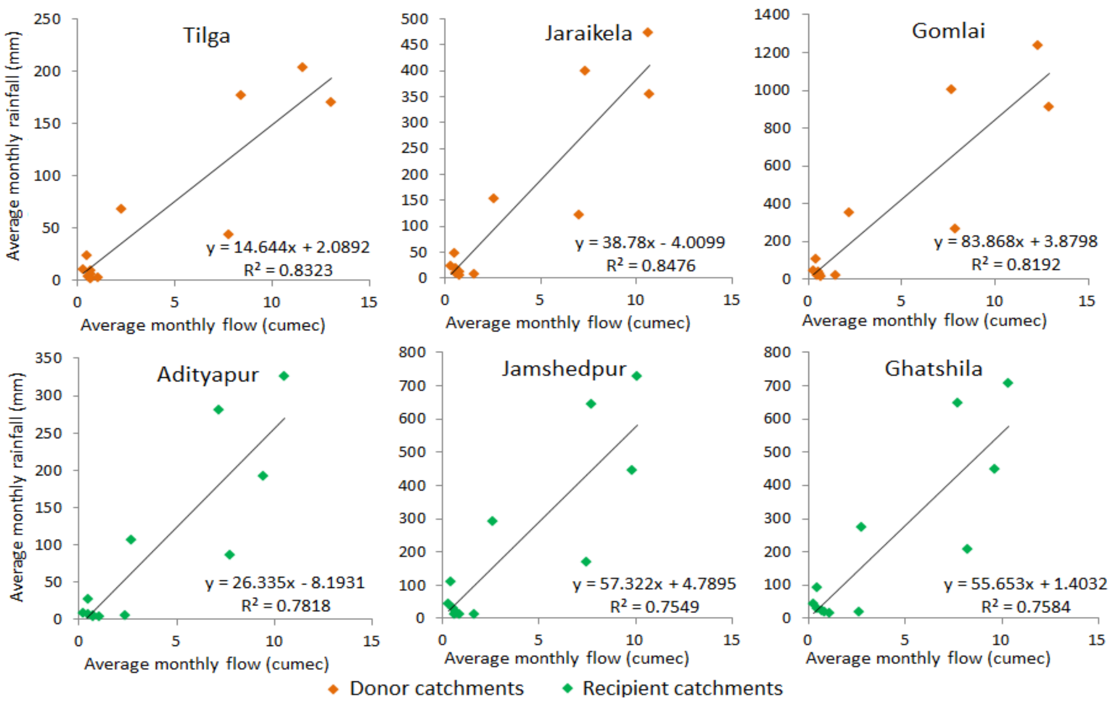


Figure 4.37: The scatter-plots of mean monthly rainfall and flow (1980-05) in the catchments.

The monthly relationship between rainfall and flow (1980-2005) was explored through their scatter-plots (linear regression) which showed high coefficients of determination as seen in Figure 4.37. When examined through cross-correlation, consecutive months of rainfall and flow showed significant cross-correlation in all catchments indicating a strong relationship between them (Figure 4.38).

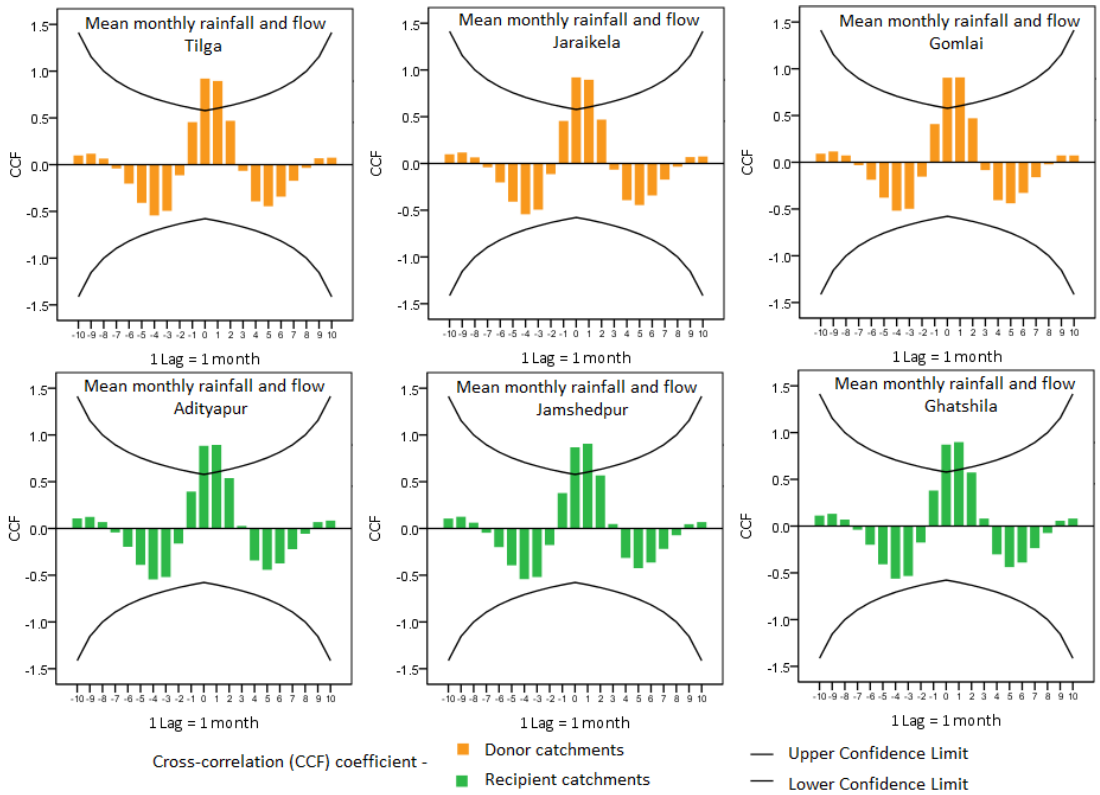


Figure 4.38: Cross-correlation between monthly mean rainfall and flow of each catchment during 1980-2005.

4.5 Socio-economic patterns

As socio-economic patterns influence water demand in any catchment, they need to be assessed as part of the decision-making for any water resource project (GWP 2009). Therefore, population and economic activities in the six catchments under study are assessed in the following sections.

4.5.1 Population dynamics

The total population of the study area is 10,166,308 of which 26% are located in urban areas (Census-GOI 2011). Jaraikela is the most populous catchment followed by Jamshedpur; Jaraikela has a greater rural population, while Jamshedpur has a more urban population (Table 4.29 and Figure 4.39).

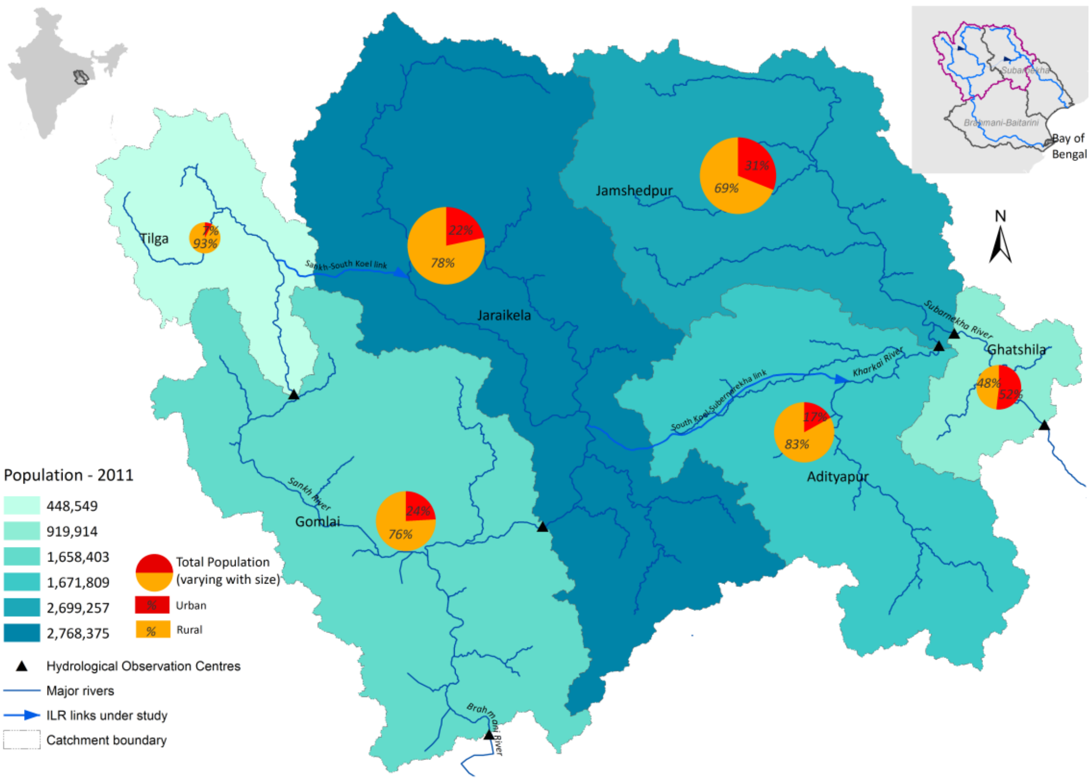


Figure 4.39: Population: total, urban (%) and rural (%) population in 2011 (Source: Census-GOI 2011).

These two catchments are followed by Adityapur and then Gomlai; however Adityapur has a more rural population while Gomlai has a more urban population. Ghatshila has the second lowest population; however, has the largest urban population percentage out of all the catchments (Figure 4.39). Tilga is the least populous and least urban (Table 4.29 and Figure 4.39). Overall 4,875,328 and 5,290,980 people lived in donor and recipient basins respectively with 21% and 30% being urban population making the recipient basin more urbanised than the donor basin.

Table 4.29: Population and growth rate (%) in catchments (Source: Census-GOI 2011).

Catchments	Population - 2011			Growth rate (%) per year - (2001-11)			Population density (2011)
	Total	Urban	Rural	Total	Urban	Rural	
Tilga	448,549	33,018	415,531	2.0	7.8	1.7	158
Jaraikela	2,768,376	598,705	2,169,671	2.3	3.0	2.1	207
Gomlai	1,658,403	400,897	1,257,505	1.6	1.9	1.5	144
Adityapur	1,671,808	283,033	1,388,775	2.0	2.9	1.9	222
Jamshedpur	2,699,257	838,241	1,861,017	2.2	3.4	1.8	290
Ghatshila	919,914	477,081	442,833	1.7	1.6	1.8	298
Donor	4,875,328	1,032,620	3,842,708	2.0	2.64	1.85	224
Recipient	5,290,980	1,598,355	3,692,625	2.1	2.72	1.82	374
Total	10,166,308	2,630,975	7,535,333	2.05	2.69	1.83	283

Total population growth rate is highest in Jaraikela, closely followed by Jamshedpur and then by Tilga and Adityapur (Table 4.29). Ghatshila and Gomlai have the lowest population growth rate. Tilga has the highest urban growth rate while Ghatshila has the lowest. Individually, urban growth rate is higher in donor catchments; however, when compared at the basin scale, the recipient basin has a slightly higher urban growth rate. Rural population growth rate is highest in Jaraikela, while lowest in Gomlai. However, it does not vary significantly among catchments. When compared at the basin scale, both basins have a similar rural growth rate.

Population density (persons per km^2) whether total, urban or rural, is high in recipient catchments and highest in Ghatshila (Table 4.29 and Figure 4.40). Ghatshila is highest followed by Jamshedpur and then Adityapur. Adityapur, the main recipient catchment, has higher total and rural population density while urban population density is higher in Jaraikela, the main donor catchment. Tilga ranks lowest among all catchments.

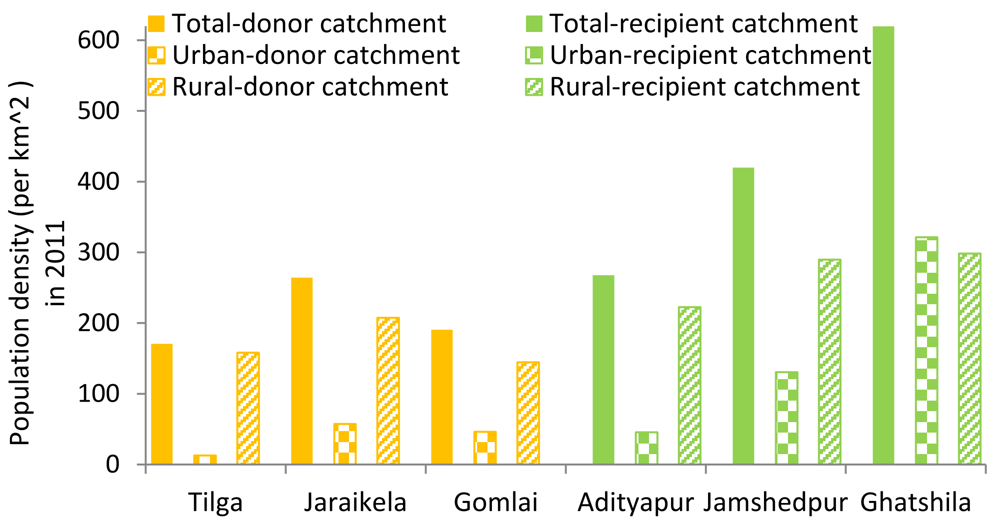


Figure 4.40: Population density (per km^2) in catchments of study area (Source: Census-GOI 2011).

The study area is pre-dominantly agricultural with 65% of the working population engaged in agricultural activities. Tilga has the highest working population, followed by Adityapur, Jaraikela and Gomlai together (Figure 4.41). Jamshedpur has the second lowest, while Ghatshila has the lowest working population.

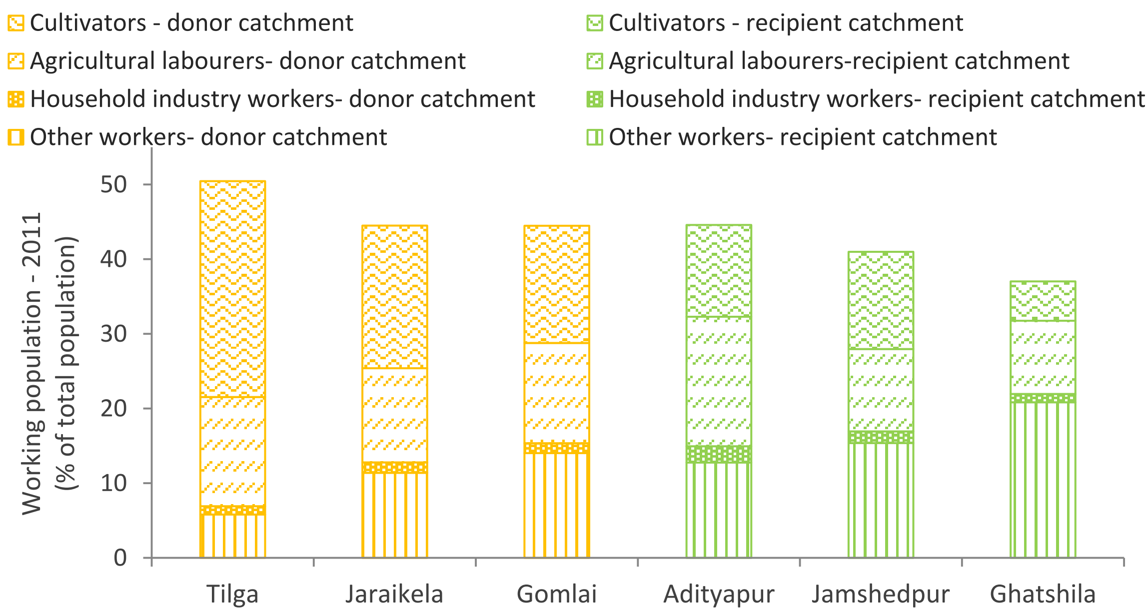


Figure 4.41: Occupational structure of study area in 2011 (Source: Census-GOI 2011).

In India, the occupational structure of the working population is classified into four occupational categories (Census-GOI 2011): cultivators (people directly engaged in cultivation), agricultural labourers (people engaged in cultivation in return of payment or share), household industries (small industries on the household level) and other workers (people engaged in other economic activity) (Bhagat et al. 2008). The population of the study area in these four categories are given in Table 4.30 and are represented in Figure 4.41.

Table 4.30: Occupational structure of population in 2011 (Source: Census-GOI 2011).

Catchments	Total workers	Total workers (% of total population)	Occupation structure (% of total workers)			
			Cultivators	Agricultural labourers	Household industry workers	Other Workers
Tilga	226,365	51	57	29	2	12
Jaraikela	1,231,792	45	43	28	3	26
Gomlai	737,641	45	35	30	3	32
Adityapur	745,555	45	28	39	5	29
Jamshedpur	1,106,218	41	32	27	4	38
Ghatshila	340,660	37	14	26	3	56
Donor	2,195,798	45	42	29	3	26
Recipient	2,192,432	41	28	31	4	37
Total	4,388,231	43	35	30	3	32

In the donor basin a significantly larger share of the working population is involved in agricultural activities than observed in the recipient basin (Table 4.30 and Figure 4.41). Tilga has the highest population engaged in agricultural activities, while Ghatshila has the lowest in agricultural activities and *vice-versa* (Table 4.30). Jaraikela follows Adityapur in non-agricultural activities despite a higher urban population percentage.

4.5.2 Agricultural activities

The study area falls completely within the agro-climatic[5] zone named the Eastern Plateau and Hills Region (EPH) (Singh 2006); it is rich in land and water, yet it has

[5] There are 131 agro-climatic zones (Singh 2006) and 20 agro-ecological regions in India (Sehgal et al. 1992).

low productivity. Agriculture is mainly rain-fed and livestock rearing is practised widely (Singh 2006). There are three cropping seasons: summer, autumn and winter (Table 4.31) (GOI 2000). The main agricultural crops are similar across catchments in which rice is the most important (Singh 2006). Except in Tilga, a large percentage of rice is grown during the winter i.e. *Kharif* season (Table 4.32) followed by autumn i.e. *pre-kharif* season. Other major crops are maize, black gram, lentils (Arhar) and vegetables (GOI 2016).

Table 4.31: Cropping seasons in India (Source: GOI 2000).

Season	Sowing months	Harvesting months
Summer (*Rabi*)	November - February	March-June
Autumn (Pre-Kharif)	May-August	September - August
Winter (*Kharif*)	June-July	November-December

Table 4.32: Rice cultivation (%) during differnt seasons (2010) in catchments.

Season	Tilga	Jaraikela	Gomlai	Adityapur	Jamshedpur	Ghatshila
Summer	0.2	0.3	0.6	1.1	0.3	1.5
Autumn	70.9	21.9	43.0	13.2	15.5	2.7
Winter	28.9	77.9	56.4	85.7	84.2	95.8

In total 47% of the study area is under agriculture. Out of the total agricultural land in donor and recipient basins, 59% and 55% of the areas respectively are cultivated, while 41% and 45% of the areas respectively are fallow land. Overall, 45% and 51% area of donor and recipient basins respectively are under cropland, making the percentage of agricultural land higher in recipient catchments (section 4.3, Table 4.2 and Figure 4.42).

Although Jamshedpur and Adityapur have significantly large populations engaged in non-agricultural activities, they have a higher percentage area under cropland (Figure 4.42). These catchments are followed by Jaraikela, Gomlai and then Tilga. Ghatshila has the smallest percentage area under crops and highest as fallow land. Apart from Ghatshila, the proportion of fallow land is high in donor catchments, despite the large percentage of population involved in agricultural activities.

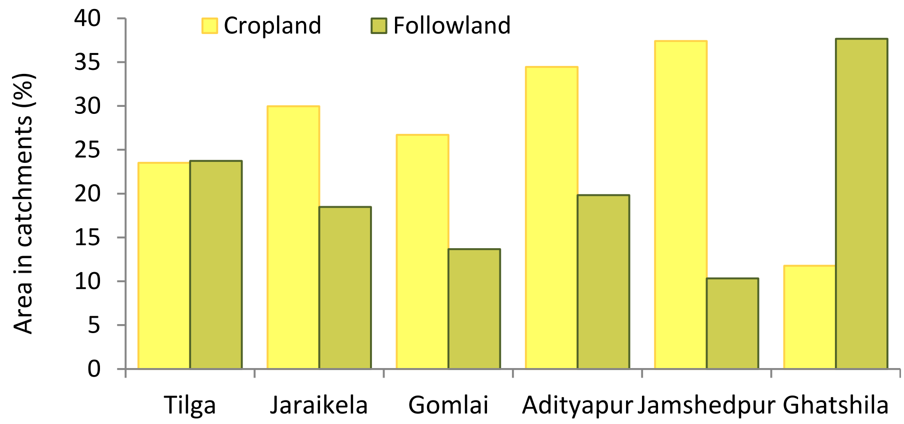


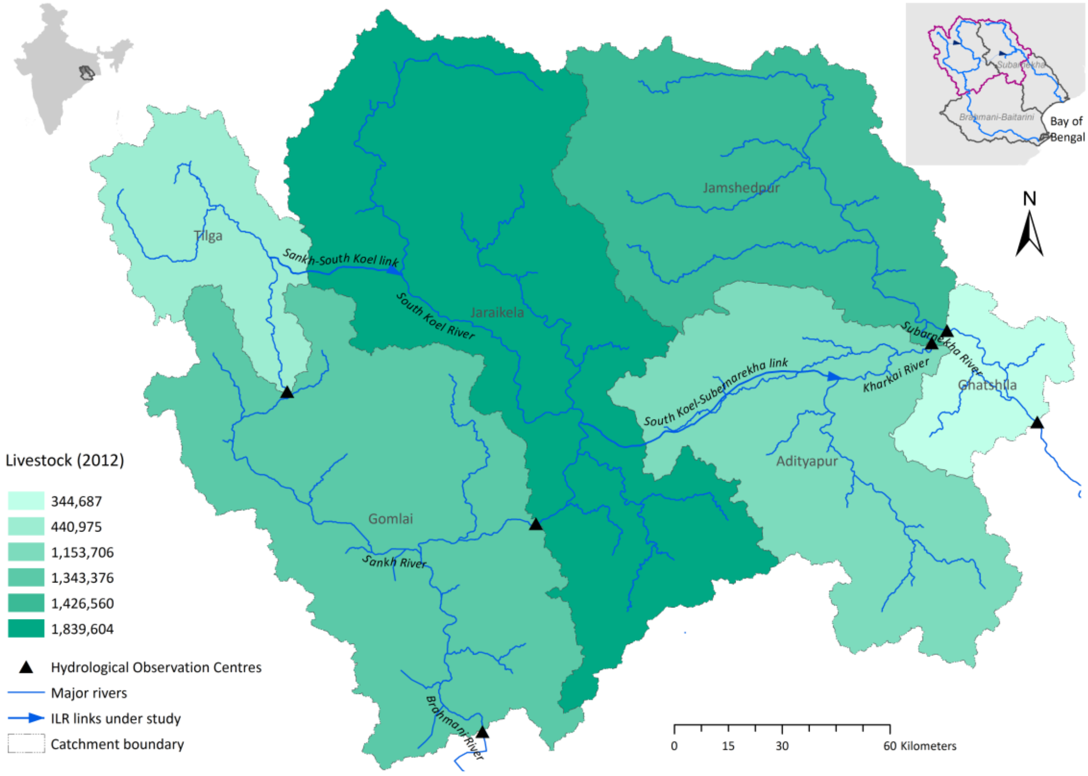
Figure 4.42: Culitvated and fallow land in catchments during 2005-2006 (Source: India-WRIS webGIS 2015)

The major livestock in the study area are cattle, goat and buffalo (Singh 2006; GOI 2016). Out of the total livestock in the study area, 50% is cattle and 36% is goat (Table 4.33). Jaraikela has the highest number of livestock, while Ghatshila has the lowest (Figure 4.43a). Overall, the donor basin has more livestock than the recipient basin.

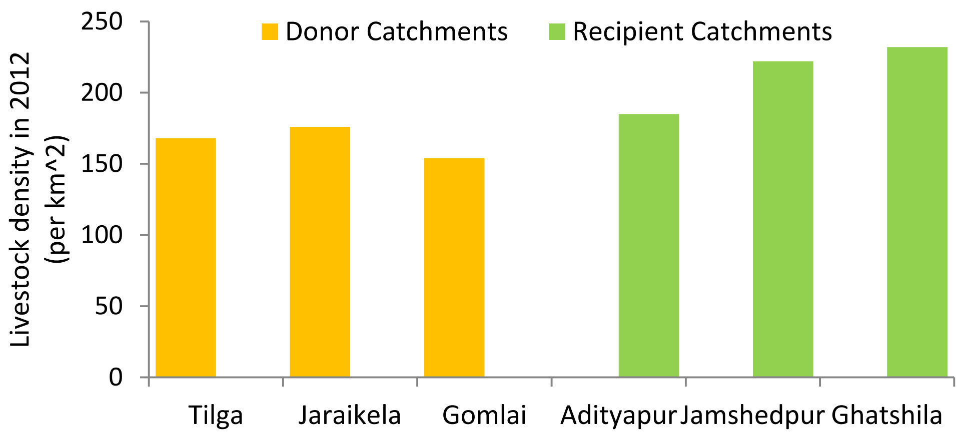
Table 4.33: Total livestock in 2012 and its type (%)

Catchments	Total	Livestock (2012) In % of total					Density (per km^2)
		Cattle	Buffalo	Goat	Pig	Sheep	
Tilga	440,975	54	7	32	4	3	168
Jaraikela	1,839,604	49	7	36	5	3	176
Gomlai	1,343,376	52	5	34	3	5	154
Adityapur	1,153,706	51	5	35	4	5	185
Jamshedpur	1,426,560	49	6	37	5	3	222
Ghatshila	344,687	49	6	37	5	3	232
Donor	3,623,955	51	6	35	4	4	166
Recipient	2,924,953	50	6	36	4	4	207

Livestock density is highest in Ghatshila and lowest in Gomlai (Figure 4.43b). Overall the donor catchments have 55% of total livestock, while recipient catchments have 45%; however livestock density is high in recipient catchments (Figure 4.43b).



(a)



(b)

Figure 4.43: Livestock (2012) in study area : (a) number (b) density (per km^2) (Source: GOI 2016)

In the study area, 13% and 33.5% of donor and recipient basin are under irrigation in 47 completed and on-going irrigation projects (Table 4.34; Appendix B.2). In the present research, the command areas for 42 irrigation projects are based on the reports by Regional Remote Sensing Service Centre (RRSSC) of GOI (Sharma et al. 2007) due to two reasons: first, several discrepancies were noted in the area given in the existing plans by NWDA (2009a, 2009b) (Chapter 3, section 3.4.1) and second, areas reported in RRSSC reports by Sharma et al. (2007) have been verified by GIS mapping. The command area of the remaining five irrigation projects are only reported by NWDA (2009a, 2009b); thus they have been taken from existing ILR plans.

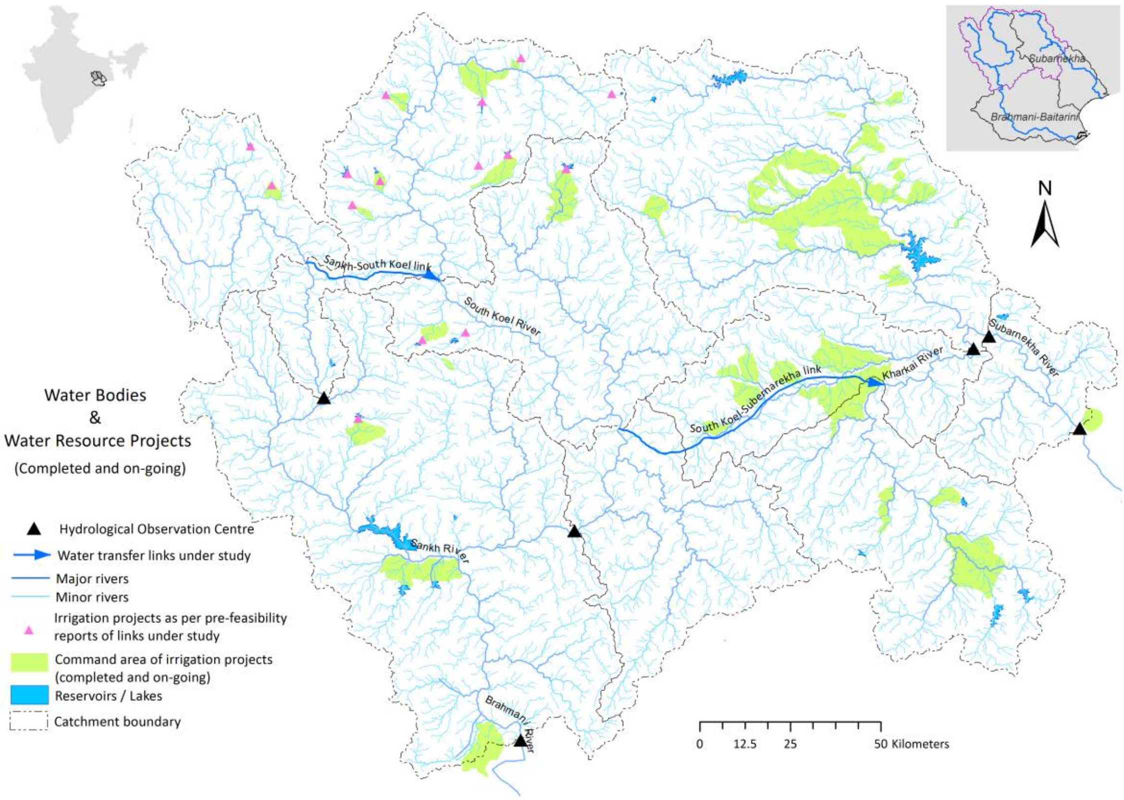


Figure 4.44: The completed and on-going Irrigation projects in the study area (details in Appendix B.2).

All completed and on-going irrigation projects are shown in Figure 4.44 (details in Appendix B.2). Out of these projects, 18 are located in donor catchments covering 577 km^2 and 29 are located in recipient catchments covering 1583 km^2. Jamshedpur has the highest percentage of cropland under completed or on-going irrigational projects, closely followed by Adityapur (Table 4.34). Ghatshila ranks third. As noted by Sharma et al. (2007), Tilga has the lowest percentage of irrigated crop land; however, when existing ILR plans (NWDA 2009a, 2009b) are taken in account, Gomlai has the least while Tilga has the most cropland under completed or on-going irrigation projects among the donor catchments.

Table 4.34: Percentage cropped area under irrigation (source: Sharma et al. 2007; NWDA 2009a, 2009b)

Catchment	Cropland (km^2)	Area of irrigation projects (% of cropland)			
		Completed and On-going			Proposed
		RRSSC	ILR plans	Total	ILR plans
Tilga	618	2.7	11.5	14.2	13.5
Jaraikela	3,139	8.9	4.6	13.5	24.9
Gomlai	2,325	12.1	-	12.1	-
Adityapur	2,151	33.4	-	33.4	-
Jamshedpur	2,405	34.8	-	34.8	-
Ghatshila	175	16.5	-	16.5	-
Donor	6,082	9.5	3.5	13.0	14.2
Recipient	4,731	33.5	-	33.5	-
Total	10,813	20.0	2.0	22.0	8.0

Overall, 33.5% of cropland in recipient basins is under completed or on-going irrigation, while the figure is only 13% in the donor basin. According to NWDA (2009a, 2009b) another, 14.2% of cropland in the donor basin is proposed to be under irrigation in future.

4.5.3 Mining and Industry

GSI (2010) and Panda et al. (2005) reported several economically exploited minerals in the study area (Figure 4.45) which require water resources. Most mines are situated in Jaraikela (downstream) and Adityapur. Tilga and Jaraikela have bauxite mines; iron ore is most abundant in Jaraikela and Adityapur; manganese mines are found in Jaraikela, Gomlai and Adityapur. Gomlai also has limestone and iron ore. Overall, Adityapur has the highest numbers of minerals and number of mines followed by Jaraikela.

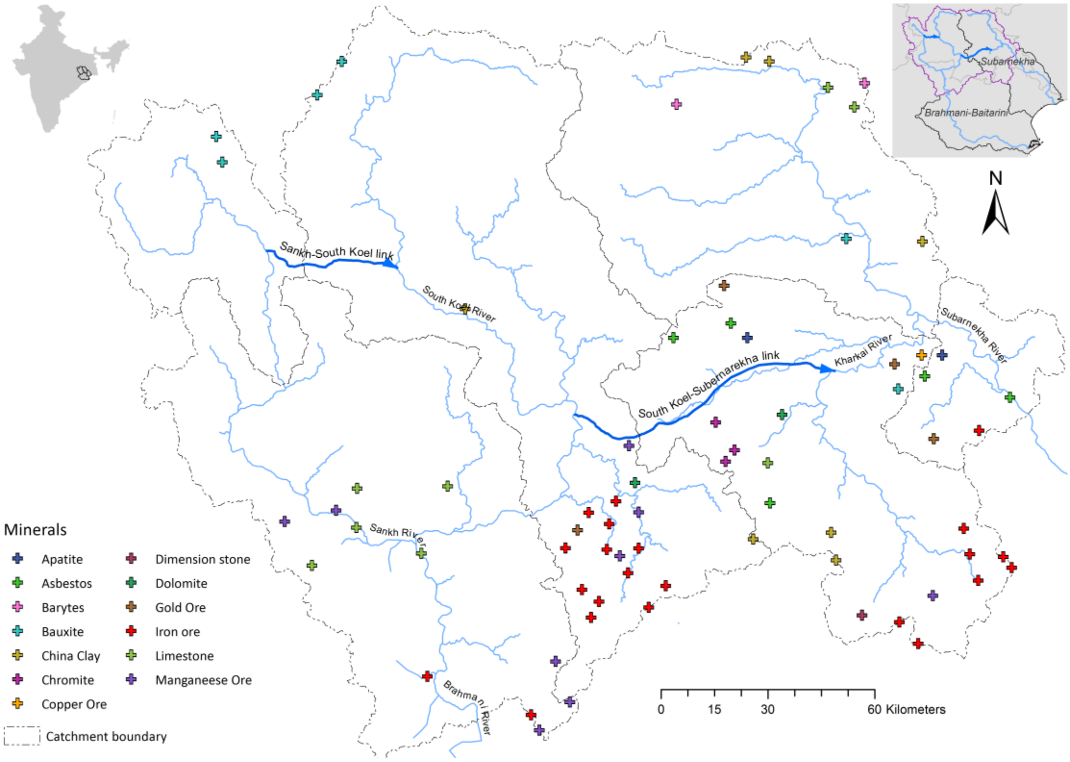


Figure 4.45: Mining areas of important minerals in catchments (GSI 2010).

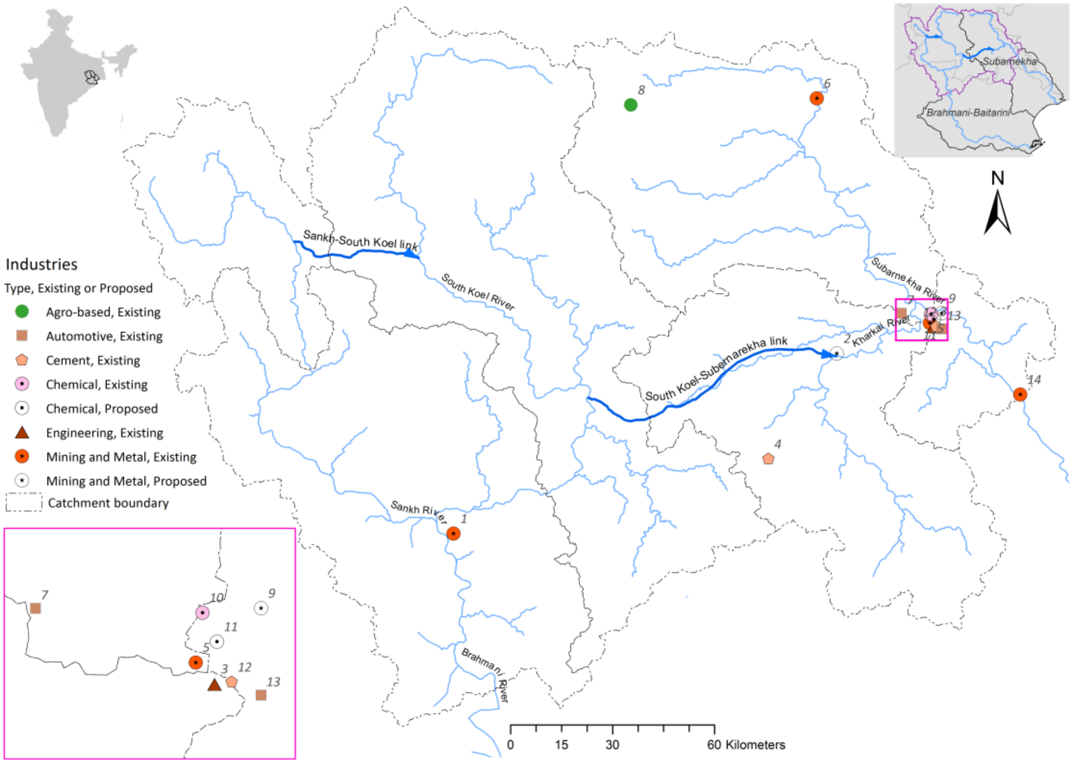


Figure 4.46: Major industries in the study area (Source: MoC&I, GOI 2016)

The Ministry of Commerce & Industry (MoC&I), GOI (2016) identified 14 major industries of which 11 are existing and 3 are proposed (Table 4.35). Out of these, 13 are located in the recipient basin while 1 is situated in the donor basin. In total 10 major industries, including 3 proposed, are located downstream of the two proposed ILR links. The only major industry in the donor basin, Rourkela Steel Plant – a public undertaking (MoC&I, GOI 2016) – is located downstream of water transfer points of the two ILR links. The only other public undertaking among these industries is 'Hindustan Copper Limited', the remainder are private undertakings (*ibid*).

Table 4.35: Major Industries in study area.

Catchment		Major Industries	Type
Gomlai			
	1	Rourkela Steel Plant	Mining and Metal
Adityapur			
	2	Tata-Greenfield integrated steel plant (proposed)	Mining and Metal
	3	TRF Limited	Engineering
	4	ACC Limited	Cement
Jamshedpur			
	5	Tata Steel	Mining and Metal
	6	Hindalco Industries Limited (HIL)	Mining and Metal
	7	Adityapur Industrial Development Area	Automotive
	8	Swastik Group	Agro-based
	9	Tata's joint venture company (proposed)	Mining and Metal
Ghatshila			
	10	Tata Pigments Limited	Chemical
	11	Air Separation Unit, Linde India (proposed)	Chemical
	12	Lafarge Cement	Cement
	13	Tata Motors Limited	Automotive
	14	Hindustan Copper Limited	Mining and Metal

Major industries are dominant in recipient catchments, with most of them located in the area named as 'Adityapur Industrial Development Area (AIDA)'. AIDA expands into parts of Adityapur, Jamshedpur and Ghatshila and also covers small and medium industries (Ministry of Micro Small & Medium Enterprises (MSME) 2016). In the study area, MSME (2016) reported a total of 297 km^2 under small and medium industries, in which AIDA covers 137 km^2 (Table 4.36). Donor catchments have 9.47 km^2 (3.2% of total) under small and medium industries and the remaining 96.8% of small and medium industrial areas is in recipient catchments.

Table 4.36: Small and medium industrial area in catchments (MSME 2016)

<table>
<tr><th>Catchments</th><th>Total Industrial Area (in km^2)</th><th colspan="2">Names of Small and medium industrial area</th></tr>
<tr><td>Tilga</td><td>0.04</td><td colspan="2">Gholeng and Harradipa</td></tr>
<tr><td>Jaraikela</td><td>1.89</td><td colspan="2">Gumla Industrial Area, Barbil and Matakambeda</td></tr>
<tr><td>Gomlai</td><td>7.54</td><td colspan="2">Rourkela, Commercial estate, Kalunga, Mandiakudar and Rajgangpur</td></tr>
<tr><td>Adityapur</td><td>0.15</td><td>Rairangpur (excluding AIDA)</td><td rowspan="3">Adityapur Industrial Development Area (AIDA)</td></tr>
<tr><td>Jamshedpur</td><td>1.64</td><td>Tupudana, Kokar, Namkum, Tatisilwai-phase I and phase-II (excluding AIDA)</td></tr>
<tr><td>Ghatshila</td><td>137.27</td><td>(represents total area of AIDA)</td></tr>
<tr><td>Donors</td><td>9.47</td><td colspan="2">-</td></tr>
<tr><td>Recipients</td><td>139.06</td><td colspan="2">-</td></tr>
</table>

4.6 Discussion

The planning and management of the S-SK and SK-Sr links need a holistic and multi-disciplinary understanding of the catchments for their sustainability, as advised by Lach et al. (2005). This study addressed the gap outlined and attempted to provide a holistic picture of the catchments involved in the two ILR projects based on their landscape, hydrology and socio-economic features which are discussed below.

The study area covers 35,963 km^2 and ranges between 65-1100 MSL; with Jaraikela being its largest catchment unit and Ghatshila the smallest catchment. The area is largely made up of plateaux and is diverse in lithology and rich in minerals. The dominant soil in the catchments is poor in quality and holds little water. The donor basin has a high percentage of forested area while the recipient basin has a high percentage of cropland. The surface water availability at 75% dependability, whether based on natural or observed flow, is higher in the donor basin than the recipient basin. Further, the donor basin has approximately 60% more ground water available than the recipient basin; however the ground water permissible for use constitutes a very low percentage of the total water available in both basins.

The catchments have monsoon climate (Rao 1979); the rainfall increases westward. The two donor catchments, Tilga and Gomlai exhibited higher rainfall but with large variation. The remaining donor catchment Jaraikela, as well as the three recipient catchments, showed similar rainfall amount. In Jaraikela, along with the other two donor catchments, the influence of extreme events was evident in the data. Further, the spatial pattern of rainfall displayed significant relationships among the catchments and highlighted a donor and recipient basin-wise pattern which was stronger in the non-monsoon season. The temporal pattern of rainfall showed seasonal and inter-annual cycles of wet-dry periods which could be related to El Niño; also suggested by Pai et al. (2011). The catchments received 80-86% of total rainfall in the monsoon season (June-September); thus the spatial and temporal patterns of the annual rainfall was governed by the monsoon rainfall (Rao 1979). However, during the lean period i.e. non-monsoon season, the recipient catchments performed better than the donor catchments. Remarkably Jaraikela, which showed similar monsoon rainfall as the recipient catchments, displayed low non-monsoon rainfall which was in line with the other two donor catchments; thus it registered lower rainfall in both seasons. This is important for the SK-Sr ILR project under study as Jaraikela is the donor catchment of the SK-Sr link, and itself gets less water when compared to other catchments in the project. Further, when examined for sudden or gradual change, none of the catchments showed any significant change in their rainfalls. Similar results were found by Singh et al. (2008) who noted that rainfall in the Brahmani and Subarnarekha river basin remained stable in the last 90-100 years.

The donor basin displayed higher flow than the recipient basin. However, the flow in the donor basin exhibited the influence of extreme events. Similar to rainfall, the flow is significantly correlated among catchments in both seasons except in one instance when the non-monsoon flow in Jamshedpur displayed an insignificant correlation with its counterparts. Further, the temporal pattern of flow exhibited seasonal and inter-annual cycles of wet-dry periods. The relationship between El

Niño and flow was stronger than that with rainfall, similarly to results presented by Jian et al. (2009) for a nearby area in the Ganga river basin. The lower statistical significance of rainfall could be attributed to its grid-based data which could have influenced the original properties of observed rainfall such as extreme events and precipitation frequencies, leading to some data-loss (Ensor & Robeson 2008). The daily rainfall data from a nearby rain-gauge station could be helpful in assessing the rainfall- El Niño relationship more accurately as this relationship is vital for water resource planning in the Indian sub-continent (Burt & Weerasinghe 2014); this could not be carried out in the present research due to its scope. Nevertheless, both rainfall and flow displayed influence of El Niño. Furthermore, the monsoon flow was significantly higher, while non-monsoon flow was only marginally higher, in the donor basin when compared to the recipient basin. However, the water yield of catchments displayed a different picture and only Tilga showed high water yield. The remaining catchments largely remained in a similar range' however, a donor and recipient basin-wise pattern was evident through the consistency of water yield which was better in donor catchments. Nevertheless, the extreme events were noted most in donors. Jaraikela showed the lowest water yield among all the catchments in both seasons which could be attributed to its rainfall patterns. Interestingly, Jaraikela displayed relatively higher flow than Tilga and Adityapur which could be explained by the large area it covers. Further, similar to rainfall, no significant sudden or gradual changes were observed in any of the catchments. However, recipient catchments registered considerable improvement in their low flow conditions which could be related to the high number of irrigation projects they have.

The rainfall and flow of each catchment, whether annual or seasonal, were highly correlated for the same year except in one instance. The non-monsoon flow in Jamshedpur showed poor correlation with the non-monsoon rainfall. However, it showed significant correlation with the monsoon rainfall of the catchment. This could be explained by either the addition from groundwater or could be due to the extensive irrigation projects in the catchments. The probability of the former explanation is low due to the rocky landscape of the catchment, and only two months' overlap between the rainfall and flow and low percentage of usable groundwater (1.4%) in the Jamshedpur catchment. However, the chances of the second explanation are strong as the catchment has considerably larger water resource projects. Nonetheless, it needs to be explored in detail which is, at present, beyond the scope of this doctoral thesis.

While analysing socio-economic dynamics, it was noted that the donor basin has a lower total, but a larger rural population than the recipient basin. Jaraikela emerged as the most populous catchment with the highest rural population share among all catchments. It also displayed a higher total as well as a higher rural growth rate; while Tilga displayed a high urban growth rate. These high growth rates indicate the future growth in water demand of Tilga and Jaraikela. Further, the donor basin has a large share of the working population, as well as the population involved in agricultural activities (including the livestock rearing) when compared to the recipient basin. It indicates that the donor basin has a primarily agricultural economy as suggested by Bhakare (2010). However, the basin has fewer irrigation projects. Although some irrigation projects are proposed for Tilga and Jaraikela, the water resources of the donor basin would remain less developed than the recipient basin, even if all projects are developed. The condition is especially difficult in Jaraikela as it experiences less rainfall and the lowest water yield in the catchment. These situations indicate that the current and future challenges of water requirements in the donor basin require attention. Given the agricultural economy and large rural population, the donor catchments need urgent development of their water resources which could also support its growing domestic water requirements.

On the other hand, the recipient basin has a higher population together with a larger urban population share which indicates high water demand in the recipient basin. Further, the large working population of the recipient basin is involved in non-agricultural activities which indicates high urbanisation as suggested by Rajput (2016). This trend is corroborated by the larger urban areas evident in the land use of the recipient basin. High urban areas indicates high domestic water requirements (van Rooijen et al. 2009) in the recipient basin. Furthermore, the higher non-agricultural working population could also be related to the increased presence of mining and industries in the recipient basin. Most of the industries in the recipient basin are large-scale industries and have high water demand as identified by CSE (2004). Additionally, the presence of mining in the recipient basin also indicates higher water requirement as suggested by Mehta (2002) and Domingues et al. (2013). Thus, the recipient basin shows a high need of water for its mining and industrial activities which has also been supported by WR-GOJ (2012). Moreover, despite the presence of mining and industrial activities, the recipient basin also showed considerable agricultural activities that are evident from its large share of cropland as well as from its high number of irrigation projects. Thus, the recipient basin displays considerably higher water requirements than the donor basin and apparently it will grow further.

4.7 Summary

This chapter provides a holistic and multi-disciplinary understanding of the study area. It outlines that the study area is largely made of plateaux and is rich in minerals but low in soil fertility. Due to the monsoon climate, most of the rainfall occurs in a span of four months (June-September). Rainfall is correlated across catchments and so is the flow, with similar wet-dry cycles in them which could be influenced by El Niño. The rainfall and flow are strongly related for the same year and show only two months' overlap. The catchments do not show any significant sudden or gradual change in their rainfall or flow. The first donor catchment, Tilga, exhibits higher rainfall and water yield; however, the second donor catchment, Jaraikela, shows lesser rainfall and flow and exhibits the lowest water yield. These finding prompts questions as to whether Jaraikela will be able to act as a donor catchment or not. Although the donor basin showed lower water requirements than the recipient basin, it indicates current and future challenges of water requirements given its less-developed water resources. The recipient basin displays extensive water requirements for almost all needs and it is apparent that these needs will grow in future.

Chapter 5: Developing an integrated assessment of water availability and demand

5.1 Chapter introduction

The present chapter addresses the third objective of this thesis and intends to develop an integrated appraisal for WA and WD in the donor and recipient catchments of the Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR links. The methodology developed estimates the surplus/deficit of water in the catchments and is used for the simulation of both ILR links and catchments in the next research stage.

Section 5.2 describes methods and material used in the present research, section 5.3-5.5 describes the outcomes of this research respectively covering WA, WD and water surplus/deficit in the catchments. The results are discussed in section 5.6.

5.2 Methods and materials

5.2.1 Method

To perform the integrated appraisal of WA and WD in the donor and recipient catchments of the two ILR links, this chapter modifies the methodology of the water-balance assessment used in the existing ILR plans (NWDA 2009a; 2009b). The modification process is comprised of a two-step process (Figure 5.1): first, set-up for the modification in existing ILR methodology and, second, the modified water balance assessment. Each component is outlined in turn.

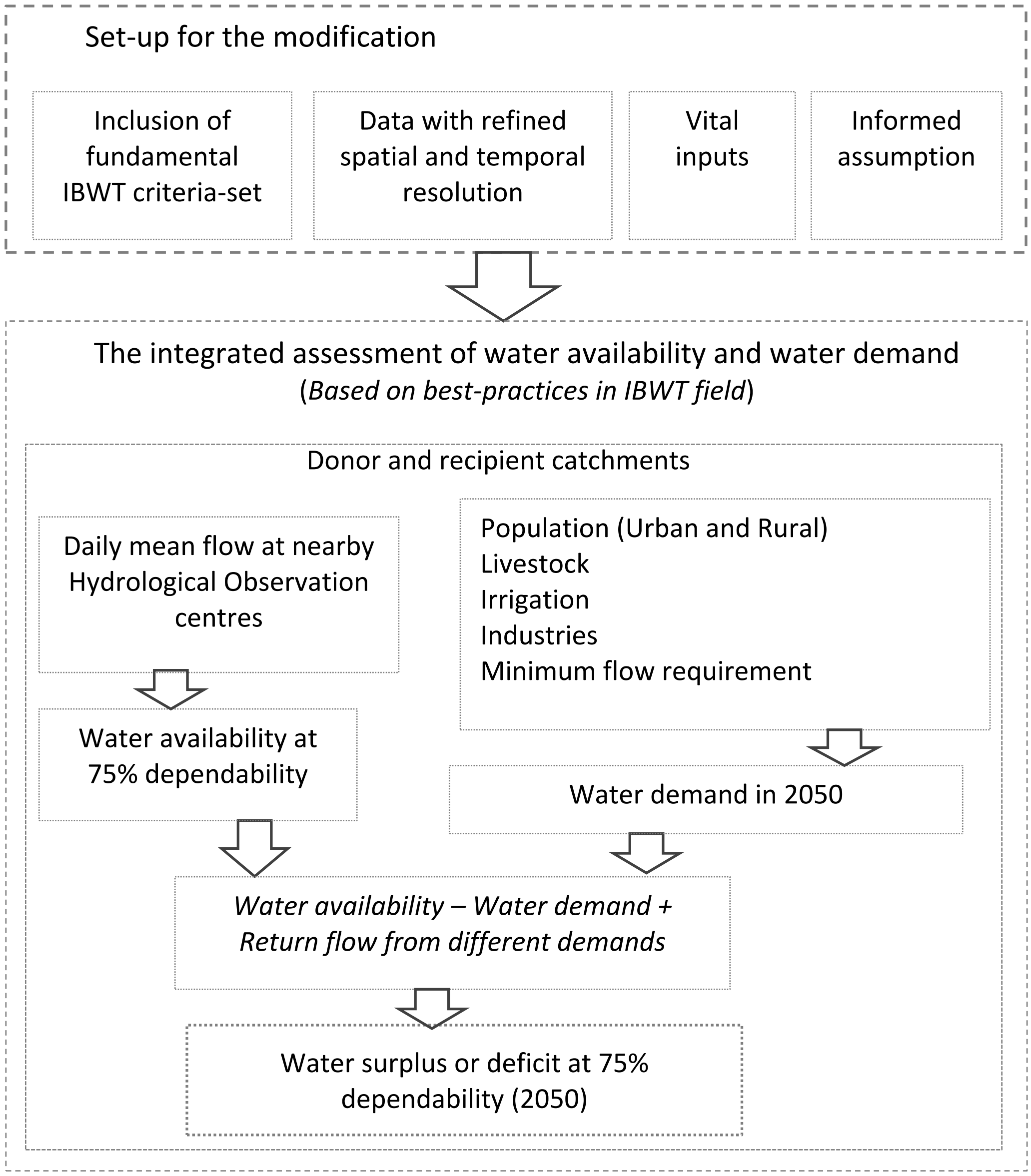


Figure 5.1: Modified version of water balance assessment process followed by NWDA (2009a; 2009b).

5.2.1.1 Set-up for the modification of ILR methodology

Inclusion of IBWT criteria by Cox (1999)

The fundamental IBWT criteria proposed by Cox (1999) was used as a basis to modify the methodology given in the ILR plans (section 2.2.4). Cox (1999) advised to finalise IBWT project only if:

- the recipient basin faces water deficits which cannot be met by its own resources, and

– the donor basin must not face any water deficit in the present or in the future due to the water transfer.

These IBWT criteria integrate the WA and WD of both donor and recipient basins and ensure their sustainability in an equitable manner. Therefore, the present research used these IBWT criteria to explore the water balance in both donor and recipient catchments.

Data with refined spatial and temporal scale

As mentioned in section 3.4.1, NWDA (2009a; 2009b) used the annual mean flow (1964-97) at Jenapur HOC to determine the WA in the catchment areas contributing to the S-SK and SK-Sr links (Figure 3.7 and Figure 3.9) despite the availability of long-term data at nearby hydrological observation centres (HOC), Tilga (for S-SK link) and Jaraikela (for SK-Sr link) (Figure 3.10 and Figure 4.1). Moreover, by taking the data available at Jenapur HOC, the ILR plans also included imported WA for the donor catchments; however, the donor catchments do not have any such current or future import. Noteworthy, the Jenapur HOC covers 37,574 km^2 and approximately 5% and 19% of its catchment-area are respectively covered by the catchment areas contributing to the S-SK and SK-Sr links. On the other hand, when compared with Tilga and Jaraikela HOC, the two catchment areas contributing to the S-SK and SK-Sr links cover 77% and 71% of the catchments of Tilga and Jaraikela respectively. Thus, the flows observed at Tilga and Jaraikela are more likely to represent the flows of the catchment areas contributing to the S-SK and SK-Sr links and could provide better WA estimation for the two catchment areas due to their finer spatial resolution (Loucks et al. 2005). Thus, the present research decided to use flow data available at Tilga and Jaraikela. Similar flow data are also used for the other catchments considered in present study (Figure 3.10 and Figure 4.1).

Further, Smakhtin et al. (2007; 2008) examined the use of annual mean flow data in estimating WA while studying the hydrological and environmental issues of the Polavaram ILR link in its donor basin. They observed that the annual data ignored the seasonal variability in WA; as a result, WA was over-estimated in the catchments of Polavaram ILR link. To avoid such WA over-estimation, Smakhtin et al. (2007; 2008) advised to include monthly WA estimation while making ILR decisions. In line with Smakhtin et al. (2007; 2008), to examine the impact of temporal resolution of the data, the current research compared mean flow data (1980-2013) at the daily, monthly and annual levels by using their respective flow duration curves in each of the catchments. Then, the study estimated annual WA at 75% flow dependability by using two datasets: the annual mean flow (AMQ) and the monthly mean flow (MMQ), and compared the two WA outcomes. Finally, the present study decided to use MMQ for its water balance assessments; the reasons for which have been explained in section 5.3.

Essential inputs and informed assumptions

Section 2.3.1.3 and section 3.4.1 outlined that the existing ILR plans ignored several essential inputs. Also, NWDA (2009a; 2009b) made assumptions without giving any reasons. To overcome these gaps, the present research used the knowledge gained through the holistic and multi-disciplinary assessments of the study area (Chapter 4), then selected the input for this research and made the required assumptions on an informed basis (Table 5.1).

Table 5.1: Assumptions made in the present research

For water availability assessment
1. The groundwater permitted to be used in the study area amounts to only 5.2% of the total WA available in the study area (section 4.3- Table 4.5). Therefore, it was not included in the water balance assessment of the catchments.
For water demand assessment 2. Livestock is one of the primary rural activities in the study area (section 4.5.2). Thus, it has been included in the water balance assessment carried out. 3. A unanimous water-use rate (NWDA 2004) has been taken for livestock despite the difference in water-use by its constituents (cattle, buffalo, goat, pig and sheep). The growth-rate is taken as given in NWDA (2009a; 2009b). 4. Due to negligible seasonal influence, domestic, livestock and industrial WD have been assumed to be equally divided for each month. 5. Similar to NWDA (2009a; 2009b), irrigation efficiency is considered to be 100% 6. Due to data unavailability, the national average of industrial water-use rate has been used in the present research. The study area includes extensively industrialised regions, thus to avoid over-estimation, only 1% per annum growth-rate of industrial WD is assumed. 7. Return flow from livestock WD is assumed to be 80%. For the remaining WD, NWDA (2004) and NWDA (2009a; 2009b) has been referred to.

5.2.1.2 The integrated assessment

Using the modification set-up mentioned above, the current ILR methodology was modified with three steps:

i) WA assessment
ii) WD assessment
iii) Potential water surplus or deficit in the catchments

Each step is described below.

i) WA assessment

To assess WA, NWDA (2009a; 2009b) annual natural flow at 75% and 50% flow dependability at the basin-scale was first calculated (Figure 3.7 and Figure 3.9) using the following Equation 5.1:

Naturalised flow = Observed flow + Net water demand + import (-)/export (+) to/from basin + Reservoir storage

Equation 5.1: The calculation for natural flow as per NWDA (2009a; 2009b).

NWDA (2009a; 2009b) used annual mean flow at 75% and 50% flow dependability (1964-97) as well as basin-scale Net WD, import and export of water and reservoir storage to calculate the natural WA at 75% and 50% flow dependability. However, they only used 75% flow dependability for the final water balance calculation (section 3.4.1). As discussed above, Smakhtin et al. (2007; 2008) found annual data ignored the seasonal variability and over-estimated the WA; thus they advised the use of monthly mean flow at 75% flow dependability to estimate WA in the catchments. However, Smakhtin et al. (2007; 2008) considered monthly flow of all the months together while calculating WA at 75% dependability which under-estimated the annual WA as they overlooked the impact of the large number of non-monsoon months (eight) in comparison to the small number of monsoon months (four) together along with the broad range of flow within the two seasons. Galkate et al. (2015) addressed this gap while studying the WA in the Kharun sub-basin (part of Mahanadi River basin). They calculated monthly WA of each of the months, at a range of flow-dependability (Equation 5.2); then, they added all the months with respective flow dependability together to get their annual WA (Equation 5.3).

$$\textit{(Monthly mean natural flow of each month at X\% flow dependability)} \times \textit{Total days in each respective month} = \textit{Monthly water availability of each month at X\% flow dependability}$$

Equation 5.2: The calculation of monthly water availability as per Galkate et al. (2015).

$$\textit{Annual water availability at X\% flow dependability} = \sum_{n=1}^{12} \textit{Monthly water availability of each month at X\% flow dependability}$$

Where, n = month
X% = flow dependability

Equation 5.3: The calculation of annual water availability as per Galkate et al. (2015).

Therefore, the method used by Galkate et al. (2015) could firstly represent the seasonal variability by using monthly data and secondly produce annual WA similar to the amount calculated from the annual data.

On the basis of these studies, the current research used MMQ datasets (1980-213) of the six HOC within the study area (section 5.2.1.1) to calculate its WA (unit: Million cubic meters i.e. MCM) and subsequently the water surplus/deficit in catchments, which is in contrast to NWDA (2009a; 2009b). Further, the current research used the flow dependability of 75% as used by NWDA (2009a; 2009b) in their final water-balance assessments. Thereby, using datasets of MMQ at 75% dependability, the present research followed Equation 5.1 and Equation 5.2 to calculate the monthly natural WA at 75% dependability for each of the six catchments under study. Then the research used Equation 5.3 to calculate the annual WA for them.

ii) WD assessment

NWDA (2009a; 2009b) assessed WD (unit: MCM) for 2050 on an annual basis, including domestic, irrigation, industry and downstream commitment to the Rengali reservoir (section 3.4.1) and ignored livestock and environmental WD (section 2.3.1.3). The present research addressed these gaps by updating their methodology for WD assessment (Table 5.2) in order to use it in the present research.

Table 5.2: Updates in the methodology of water demand assessment by NWDA (2009a; 2009b) in the current research

Water demand	NWDA (2009a; 2009b)	Present Research
Domestic	Used: population for 2001; Growth–rate: total population growth rate from UN estimates (1992/1994) and used urban population % in total population given in UN estimates 1992; Water-use rate- Urban-170 litres/capita/day Rural– 50 litres/capita/day	Used: population for 2011(Census-GOI 2011); Growth rate (for both Urban and Rural)– Based on population growth rate during 1981-2011 from Census of India (Census-GOI 2011); Water-use rate most commonly used by NWDA (e.g. NWDA (2004))- Urban – 200 litres/capita/day Rural – 70 litres/capita/day
Irrigation	WD by irrigation projects, compiled from different government reports, used different water-use rate in different reports.	Used: command area of irrigation projects in the study area (India-WRIS 2012; NWDA 2009a; 2009b); Used average of different water-use rate used in reports by NWDA (2009a; 2009b) based on principle crop, climate, soil and slope (Punmia 1992).
Livestock	Calculated using livestock data for 1980s-90s and growth rate of 1%; did not clarify livestock water use rate; did not include in final WD assessment	Used: livestock population of 2012; Water-use rate most commonly used by NWDA (e.g. NWDA (2004)) - 50 litres/capita/day. Livestock growth rate – 1% similar to NWDA (2009a; 2009b)
Industry	Equivalent to domestic WD by citing non-availability of data	Used: industrial area given by Ministry of Micro Small & Medium Enterprises (MSME 2016); Water-use rate- used national average industrial water-use rate (FAO (2015). Verified using WR-GOJ (2012). Growth-rate – 1% (Table 5.1)
Environmental	Not included; considered downstream commitment for Rengali reservoir	Based on Smakhtin & Anputhas (2006) as advised by IIT (2011); did not consider downstream commitment for Rengali reservoir at this stage

Similar to NWDA (2009a; 2009b), the current research included water requirements of domestic, irrigation and industry in its WD assessment for 2050. Further, it included livestock WD (Cai & Rosegrant 2002) and environmental WD (MoEF, GOI 2006). Moreover, it updated the datasets used as outlined in Table 5.2. The calculation of each WD included in the present thesis is described below.

Domestic WD

Urban and rural population of each catchment were projected for 2050 and then they were multiplied by their respective water-use rate (Table 5.2). The monthly distribution of domestic WD was calculated by dividing the annual domestic WD equally into all months of year (Table 5.1).

Livestock WD

Livestock rearing is an important part of rural activities in the study area (Singh 2006); thus it was included in the WD assessment of the present research. The livestock population for 2050 was projected. Then, to estimate the livestock WD, the projected livestock was multiplied with its water-use rate (Table 5.2). To estimate monthly distribution, livestock WD was equally distributed among each month of the year (Table 5.1).

Irrigation WD

The annual irrigation WD for 2050 was calculated by multiplying the catchment areas of irrigation projects (completed, on-going irrigation and proposed) by the irrigation annual water-use rate (Table 5.2). Then monthly variation of irrigation WD was calculated on the basis of cropped area (Rice) in different seasons (GOI 2016) using Zawawi et al.(2010). Here it should be noted that rice is the main crop grown in the region (section 4.5.2) and agriculture is mainly rain-fed (Singh 2006), common in monsoon months (GOI 2000). Thus, irrigation water is only needed in non-monsoon months (GOI 2016).

Industrial WD

Industrial WD for the donor and recipient basin in Jharkhand state was reported by WR-GOJ (2012). As it only covered Jharkhand state, it was not used in the present research as the study area also covers some parts of other states (section 3.4.2). Instead, industrial WD was calculated by multiplying the industrial area within the study area by the national average industrial water-use rate (Table 5.2). Two data sources were considered to provide an estimate of the extent of industrial regions in the study area: first, MSME (2016) which gives the industrial area in 2011-12 and second, the mining and industrial area extracted from land use (2005-06) prepared by India-WRIS webGIS (2016). Both estimates were verified using data from WR-GOJ (2012). The industrial WD calculated from MSME (2016) was similar to that of WR-GOJ (2012) in the catchment areas within Jharkhand, therefore it was used in the present study and was projected for 2050 (Table 5.1). The monthly distribution of industrial WD was calculated by dividing the industrial WD of 2050 equally in all months of year.

Environmental WD

As discussed in section 2.2.2.2 and 2.3.2.2 (point-ii in both sections) the environmental needs of the rivers and catchments must be covered while planning any water project. However, NWDA (2009a; 2009b) ignored this essential water demand when assessing the water balance in existing ILR plans. Instead, they included the downstream commitment of donor catchments, which was calculated on the basis of area-based share of the catchment in the total water contributing to the Rengali reservoir, located downstream of the donor catchments (see section 3.4.1). The present research included environmental WD instead of the downstream commitments as required by MoWR, GOI (2002) and MoEF, GOI (2006) while planning any water resource project in order to maintain the adequate environmental flow in the rivers (section 2.2.2.2 and 2.3.2.2). To calculate this environmental WD, the present research used Smakhtin & Anputhas (2006) as advised by IIT (2011). Smakhtin &

Anputhas (2006) considered the Brahmani River as moderately modified (class C) while the Subarnarekha River as largely modified (class D). Therefore, the monthly flows of Brahmani and Subarnarekha Rivers at 99% and 95% flow dependability respectively were used to calculate their corresponding monthly environmental WD. The total sum of all monthly environmental WD was used as their annual environmental WD.

Finally, total WD was calculated for each of the catchments by keeping the fact in context that the natural flow has been used to calculate the WA in the catchments. Therefore, for Tilga, Jaraikela and Adityapur, all the above WD estimates at the annual and monthly level were directly added together as these three catchments did not get flow from any other catchment under study. However as mentioned in section 4.2.1, Gomlai, Jamshedpur and Ghatshila got flow from other catchments; therefore, for these three, total WD was calculated within their contributing catchment area i.e. their total WD included domestic, livestock, irrigation and industrial WD of all contributing catchments other than the environmental WD measured at their outflow points.

iii) Potential surplus or deficit of water in the catchments

Similar to NWDA (2009a; 2009b), the WA and WD of each donor and recipient catchment were used to calculate the surplus/deficit of water at 75% flow dependability. In order to integrate WA and WD first, return flow was calculated for each relevant WD at both the annual as well as at the monthly level (Table 5.3). Then these regenerated flows were added together at the respective annual and monthly level to obtain total water regenerated (TWR) at annual and monthly level.

Table 5.3: Return flow (%) from different water uses (Source: NWDA 2004; NWDA 2009a; 2009b)

Water demand (MCM)	Return flow (%)
Domestic	80
Irrigation	10
Livestock (Table 5.1)	80
Industry	80

Then for each catchment, at annual and monthly level, potential surplus or deficit of water at 75% flow dependability was calculated using Equation 5.4:

$$\text{Water Surplus/Deficit} = WA - WD^{*} + TWR$$

Where, WA = total water available at 75% flow dependability
WD = total water demand as per their contributing area*
TWR = total water regenerated from different water demands

Equation 5.4: The calculation for potential surplus or deficit of water in catchment as per NWDA (2009a; 2009b).

After calculating potential annual and monthly surplus/deficit of water at 75% dependability, all catchments were explored for their fulfilment of the fundamental IBWT criteria by Cox (1999).

5.3 Results: Water availability (WA)

The present research compared catchment-scale daily, monthly and annual level mean flow data (1980-2013) using their flow duration curves in each of the catchments under study (Figure 5.2). It was observed that the distributions of daily and monthly mean flow data were similar during the study period (Figure 5.2) which suggests that the monthly mean flow (MMQ) data reflected the flow distribution during 1980-2013 relatively well, indicating their capability to address the seasonal variability. Annual mean flow (AMQ) data differed significantly from the daily and monthly mean flow in representing the flow-distribution, indicating its inability to represent the seasonal variability in flow (Figure 5.2). Further, the influence of data resolution on the estimation of annual WA was examined by estimating annual WA using the two datasets: AMQ at 75% dependability as well as MMQ at 75% dependability (during 1980-2013). The two resultant annual WA, when compared, indicated that the annual WA calculated from AMQ data is considerably higher than the same calculated from MMQ data (Table 5.4). Thus, these investigations demonstrated that the MMQ data is most appropriate for the water-balance assessments in the present research.

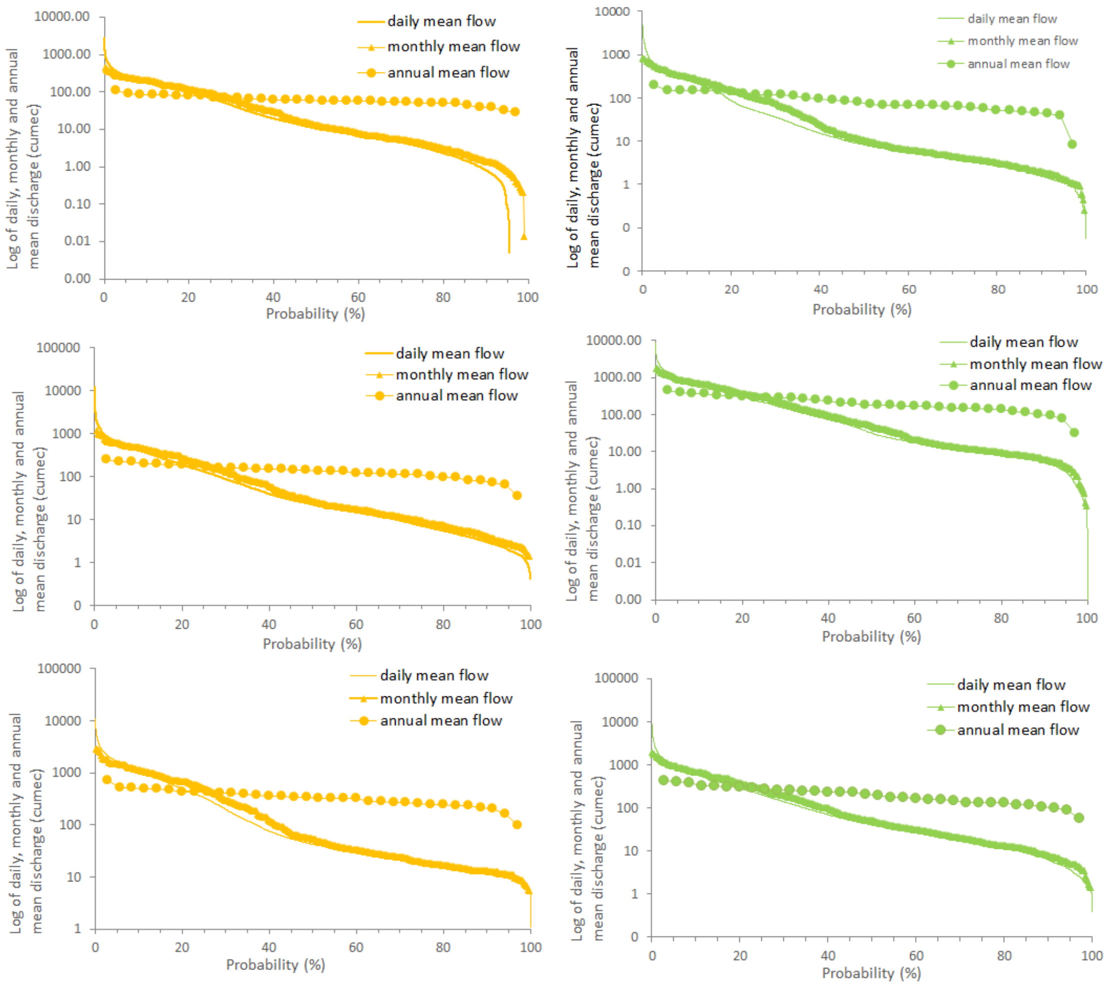


Figure 5.2: Comparison of daily, monthly and annual mean flow (1980-2013) using their flow duration curves in the catchments under study.

5.3.1 Annual WA

The annual natural WA at 75% flow dependability (1980-2013) in the catchments, using both AMQ and MMQ datasets, are given in Table 5.4. The comparison of annual WA from AMQ and MMQ led to the selection of MMQ data for the water-balance assessments in this thesis. Therefore, from here onward, the results based on MMQ data are given and discussed.

Table 5.4 shows that the annual WA was higher in the donor basin (represented by Gomlai) when compared to the recipient basin (represented by Ghatshila). As discussed in section 4.4.2, the Jamshedpur and Ghatshila HOC are in close proximity (approximately 42 km^2 apart), therefore, the two showed similar WA (Table 5.4).

To compare the WA across the catchments, the present research calculated natural WA per km^2 of the total contributing catchment area. The WA per km^2 was highest in the catchment of Jamshedpur and then in Tilga while lowest in the Jaraikela catchment (Table 5.4). The Adityapur catchment was closely followed by the Jaraikela catchment. When compared at basin scale, WA per km^2 was slightly better in the donor basin (Table 5.4).

Table 5.4: Annual water availability (MCM) at the 75% flow dependability (1980-2013) in the catchments under study.

	Natural WA (MCM) at 75% flow dependability based on		Natural WA (MCM) per km^2 of the total contributing catchment area based on MMQ
	Annual mean flow (AMQ)	Monthly mean flow (MMQ)	
Tilga	1,659	1,254	0.477
Jaraikela	3,961	2,679	0.256
Gomlai	8,615	6,925	0.318
Adityapur	2,293	1,671	0.268
Jamshedpur	7,247	6,313	0.498
Ghatshila	6,770	6,327	0.447
Donor basin	8,615	6,925	0.198
Recipient basin	6,770	6,327	0.191

5.3.2 Seasonal and monthly WA

The monthly distribution of WA at 75% flow dependability outlined the influence of the monsoon climate (section 4.4.2) as seen in Figure 5.3. The monthly WA of all catchments was higher in monsoon months (June-September) which started declining from September; it remained relatively higher in October than other non-monsoon months (Figure 5.3). Gomlai showed higher monthly WA during monsoon months and was closely followed by Jamshedpur and Ghatshila. During non-monsoon months, Jamshedpur and Ghatshila overtook Gomlai. Jaraikela displayed higher WA than Adityapur and Tilga during June-January; in February-May Adityapur was higher (Figure 5.4).

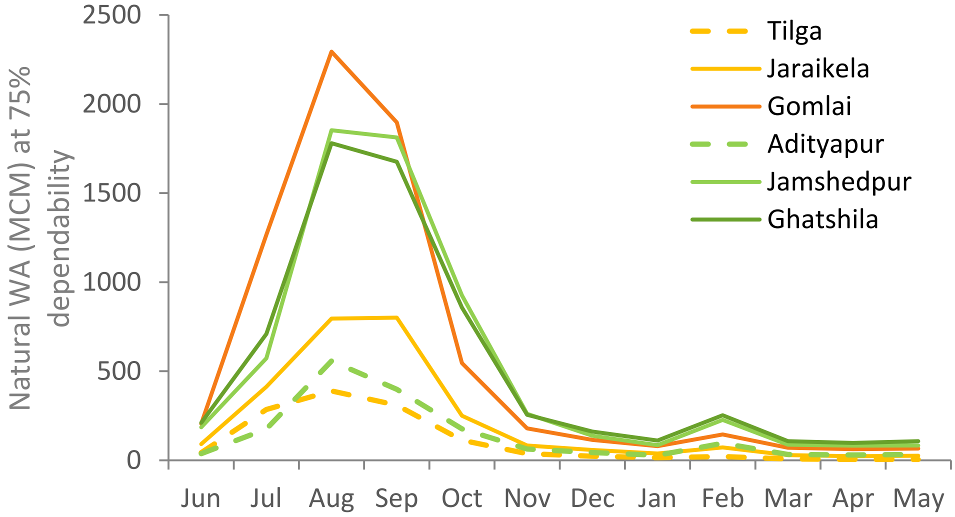


Figure 5.3: The monthly water availability at 75% flow dependability (1980-2013) in the catchments under study.

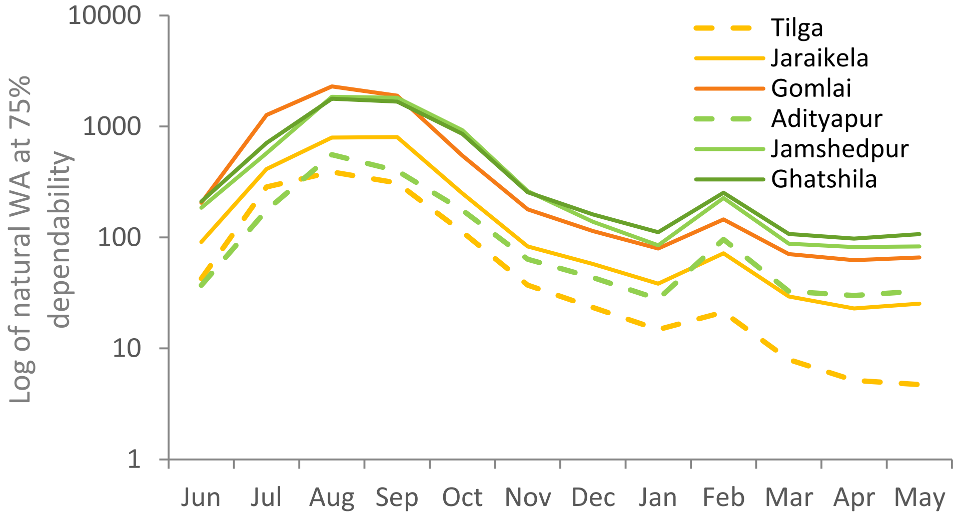


Figure 5.4: Logarithmic plot of the monthly water availability at 75% flow dependability (1980-2013) in the catchments under study.

When adjusted for the contributing catchment area, Jamshedpur and Ghatshila catchments exceeded all other catchments in monthly WA per km^2 during September-May (Figure 5.5). They were surpassed by Tilga catchment during June-August and by Gomlai catchment during July. Tilga followed Jamshedpur and Ghatshila during September-January but Adityapur replaced Tilga during January-May (Figure 5.6). Tilga has the least WA of all catchments during March-May. Gomlai and Jaraikela displayed the lowest WA per km^2 from October to March and were joined by Tilga during March-May. Recipient catchments showed better WA per km^2 than donor catchments during February-May (Figure 5.6).

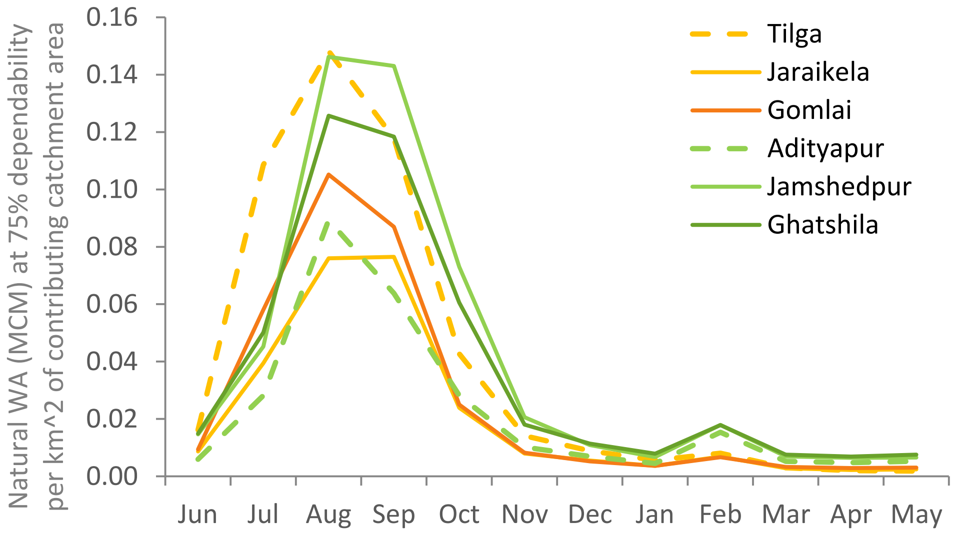


Figure 5.5: The per square kilometre monthly water availability of the catchments at 75% flow dependability (1980-2013).

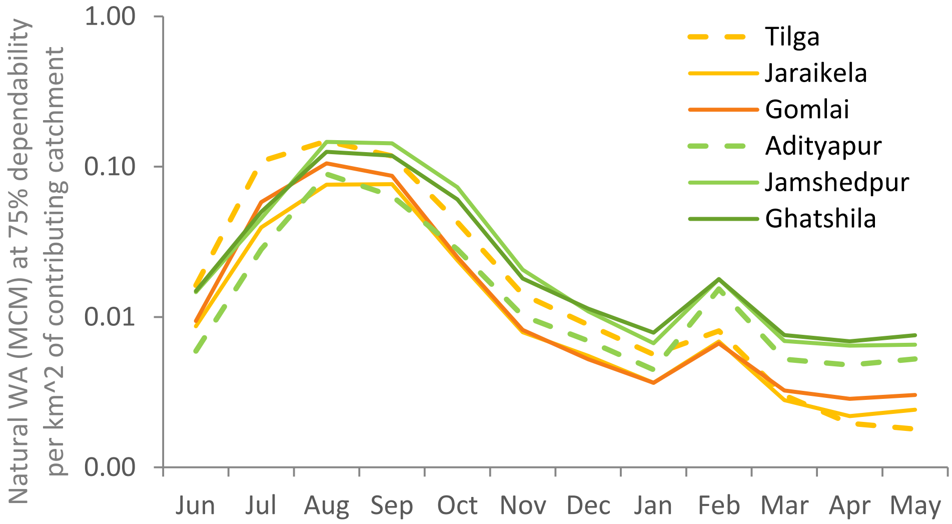


Figure 5.6: Logarithmic plot of the per square kilometre monthly water availability of the catchments at 75% flow dependability (1980-2013).

5.4 Results: Water demand (WD)

The WD of domestic, livestock, irrigation, industry and environmental needs were projected for each catchment for the year 2050. Results were analysed on an annual and monthly basis.

5.4.1 Annual WD

Table 5.5 presents projected annual WD of each catchment for domestic, livestock, irrigation, industry and environment for 2050 while Table 5.6 presents projected total WD of each catchment, calculated on the basis of the total contributing catchment area of their respective HOC (i.e. catchment area up to the gauge).

Table 5.5: Projected annual water demand (MCM) in 2050 for the catchments

	Water demand (MCM)						
	Domestic	Urban	Rural	Livestock	Irrigation	Industry	Environmental
Tilga	21	10.7	10.5	5.9	86	0.4	664
Jaraikela	197	135	62	25	607	16	991
Gomlai	89	61	28	18	141	64	2942
Adityapur	95	58	37	15	362	1.3	424
Jamshedpur	247	200	47	19	421	14.0	976
Ghatshila	75	64	11	4.6	14	1170	1273
Donor	308	207	101	48	834	81	2942
Recipient	417	322	96	39	797	1185	1273

Table 5.6: Projected total WD (MCM) in 2050 for the catchments (based on their total contributing catchment area)

	Total WD (based on total contributing catchment area)
Tilga	777
Jaraikela	1,836
Gomlai	4,213
Adityapur	897
Jamshedpur	2,151
Ghatshila	3,712
Donor	4,213
Recipient	3,712

Jamshedpur displayed the highest domestic WD, including the urban share of domestic WD, followed by Jaraikela (Table 5.5). Rural share of domestic WD was high in Jaraikela. Jaraikela also showed high WD for livestock and irrigation. Industrial WD was high in Ghatshila. However, here it should be noted that industrial WD of Ghatshila included WD for the Adityapur Industrial Development Area (AIDA) which is located at the junction of the three recipient catchments, with some of the industrial area in all three catchments (section 4.5.3). Both Gomlai and Ghatshila represented environmental WD as well as total WD for both donor and recipient basins respectively (Table 5.6). Gomlai represented the highest environmental WD and as a result its total WD was higher than Ghatshila (Table 5.5 and Table 5.6).

5.4.2 Seasonal and monthly WD

As mentioned in Table 5.1, domestic, livestock and industrial WD are equally divided into all months. Therefore, monthly variation of WD was influenced by irrigation and environmental WD (Figure 5.7 and Figure 5.8 respectively). Irrigation WD only influenced non-monsoon months (Figure 5.7).

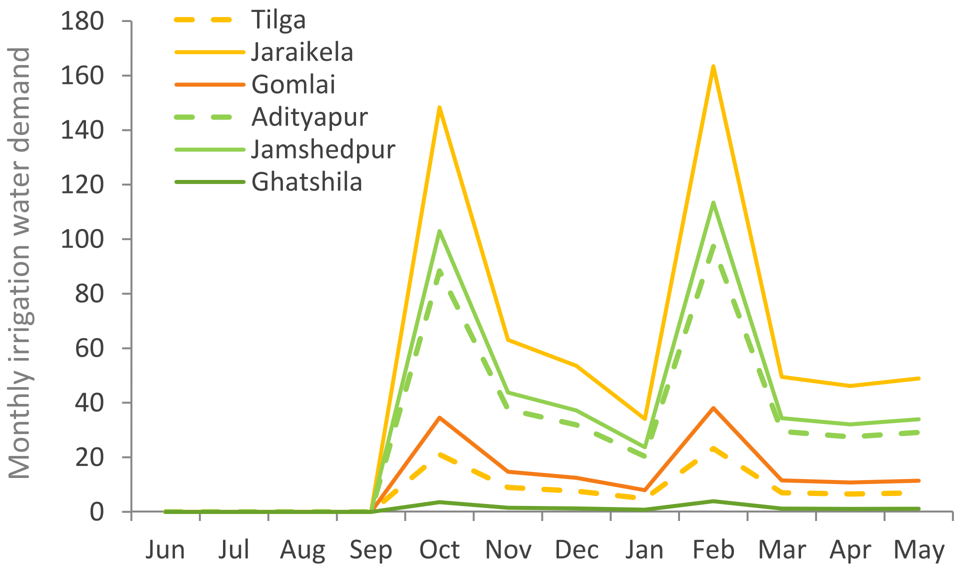


Figure 5.7: Projected monthly irrigation WD (2050) of all catchments.

However, environmental WD influenced all months, albeit with minimal influence during non-monsoon months (Figure 5.8).

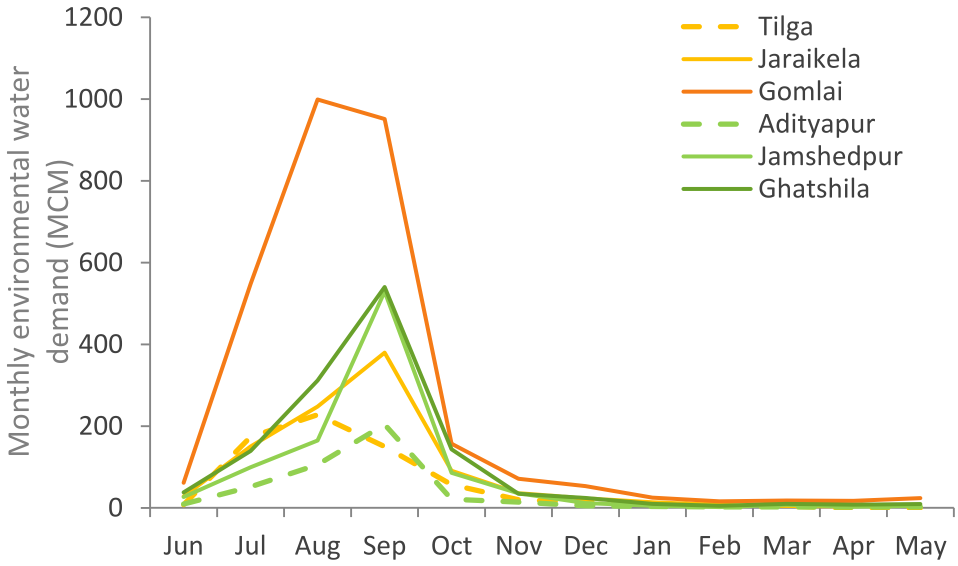


Figure 5.8: Projected monthly environmental WD (2050) of all catchments based on their monthly minimum environmental requirements.

Due to high environmental WD during monsoon months, the catchments displayed high monthly WD during those months (Figure 5.9).

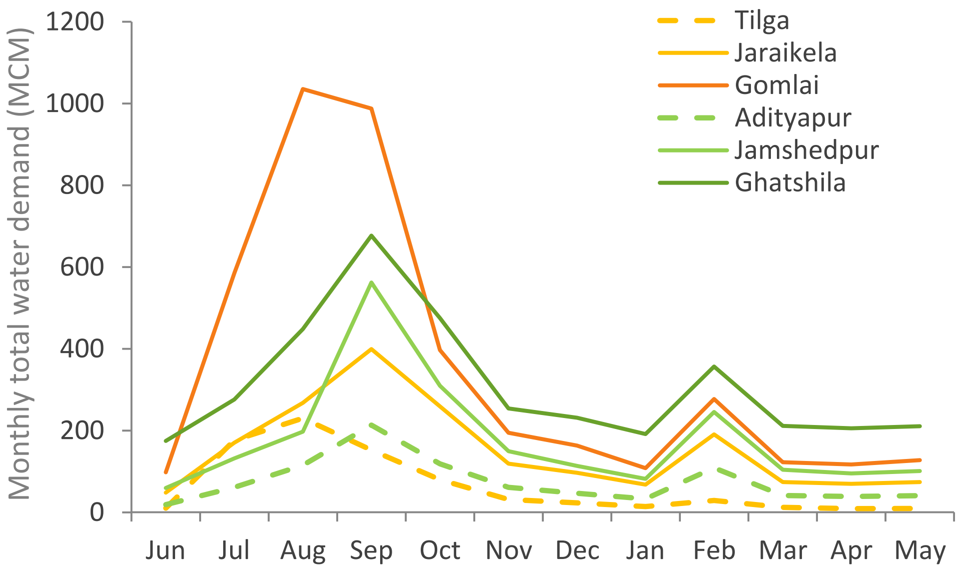


Figure 5.9: Monthly water demand (MCM) in the catchments (based on their total contributing catchment area)

The monthly WD in non-monsoon months was influenced by irrigation WD and therefore was high in the month of February (Figure 5.7 and Figure 5.9). Gomlai showed the highest WD among all catchments during monsoon months, followed by Ghatshila. In non-monsoon months Ghatshila has the highest WD, which is due to its high industrial WD, followed by Gomlai. These two catchments were generally followed by Jamshedpur, except during July-August when Jaraikela and Tilga overtook Jamshedpur, which could be attributed to their high environmental WD. Jamshedpur then by Jaraikela during September-May and Jaraikela was followed by Adityapur during the same period. Tilga showed the least relative WD among all catchments except during July-August as previously discussed. Overall, monthly WD of the donor basin (represented by Gomlai) was high in monsoon months, while monthly WD of the recipient basin was high in non-monsoon months (represented by Ghatshila).

5.5 Results: Water surplus or deficit

Similar to WA and WD, potential surplus or deficit of water at 75% dependability for each catchment was also calculated on both an annual and monthly basis.

5.5.1 Annual surplus or deficit

All the catchments displayed surplus water at 75% flow dependability (Table 5.7).

Table 5.7: Annual water surplus (MCM) of each catchment at 75% dependability

	Annual water surplus (MCM) at 75% dependability
Tilga	506
Jaraikela	1,082
Gomlai	3,128
Adityapur	893
Jamshedpur	4,538
Ghatshila	3,991

The donor basin showed less surplus water than the recipient basin, due to their high environmental requirement. Adityapur, the main recipient catchment, has less surplus water than the main donor catchment Jaraikela. Ghatshila, which is located downstream of Jamshedpur, showed less water surplus than the Jamshedpur. This pattern is likely to be attributed to the high industrial WD in Ghatshila due to AIDA which includes some industrial WD for the remaining two recipient catchments as discussed in section 5.4.

5.5.2 Seasonal and monthly surplus or deficit

The monthly surplus or deficit of water in catchments is presented by monsoon and non-monsoon seasons (Figure 5.10).

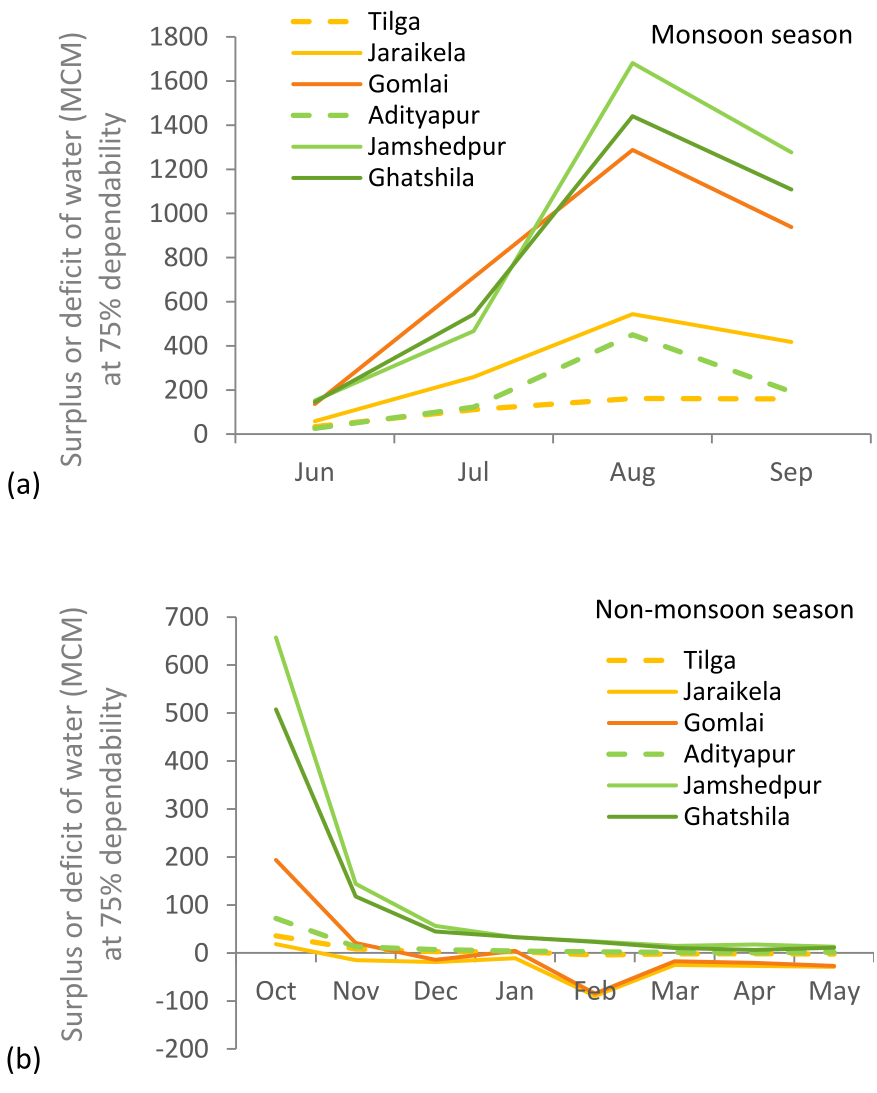


Figure 5.10: Monthly surplus or deficit of water at 75% dependability in the catchments as per seasons: (a) monsoon and (b) non-monsoon.

In the monsoon season, Gomlai exceeded all catchments during June-July with the highest water surplus followed by Jamshedpur and Ghatshila (Figure 5.10a). During August-September, Jamshedpur and Ghatshila overtook Gomlai and other following catchments and had the highest surplus in non-monsoon season (Figure 5.10b). The donor catchments showed a sharp decrease and became water deficient during December-May. The recipient catchments Jamshedpur and Ghatshila remained in surplus; however, their water balance decreased below 50 MCM during December-May while Adityapur remained near zero surpluses during November-May.

5.6 Discussion

This chapter attempted to develop an integrated appraisal of WA and WD on an annual and monthly basis in the catchments of the two ILR projects in order to examine if those catchments fulfil the fundamental criteria of IBWT decision-making or not. The annual and monthly WA of each catchment at 75% dependability (1980-2013) were calculated and compared. Then, the WD of the catchments was projected on an annual and monthly basis for the year 2050. Subsequently, the catchments were evaluated on an annual and monthly basis for the surplus or deficit of water. The outcomes are discussed here in order to examine whether the catchments fulfil the fundamental criteria of IBWT decision-making (Cox 1999).

The research noted that among annual, monthly and daily mean flow data, the monthly mean flow (MMQ) data could represent the flow-distribution fairly similarly to daily flow; therefore, it was capable of addressing seasonal variability. Moreover, the two different annual WA calculated from AMQ and MMQ outlined that the AMQ data could over-estimate the annual WA as a result of their failure in addressing the flow-distribution caused by seasonal variability. Smakhtin et al. (2007; 2008) also found similar results while assessing WA of Polavaram ILR link. Thus, by exploring the influence of spatial and temporal scales of dataset on the estimation of WA, the research found MMQ data at the catchment-scale to be suitable for the water-balance assessments. By using these data, the present study addressed the catchment-scale influence as well as the seasonal variability in the hydrological behaviour of the catchments. Also, it could avoid the basin-scale import of water as carried out in existing ILR plans.

5.6.1 Water available in the catchments

The findings suggests that the annual natural WA at 75% dependability was higher in the donor basin than the recipient basin, in line with the observations made by NWDA (2009a; 2009b). As expected, all catchments demonstrated the influence of their hydrological behaviour in the monthly and seasonal WA, showing higher WA in the monsoon months and lower WA in the non-monsoon months (section 4.4). Overall, the donor basin continued showing high WA in monsoon months but was overtaken by the recipient basin in non-monsoon months. Jaraikela, the main donor catchment, displayed higher monthly WA than Adityapur, the main recipient catchment during June-January. However, during February-May, Adityapur surpassed Jaraikela. Therefore, the seasonal distribution of WA in study area indicates that recipient catchments are likely to have more WA in non-monsoon months than the donor catchments. This seasonal influence was ignored by NWDA (2009a; 2009b). The catchments differed in WA per km^2 on an annual and monthly basis. The annual WA per km^2 was second highest in Tilga and lowest in Jaraikela, which could be explained by their hydrological behaviour (section 4.4). The monthly WA per km^2 was highest in Jamshedpur and Ghatshila in most months except June-August. In June-August, Tilga displayed the highest WA per km^2 which rapidly declined in all other months, falling below all catchments during March-May, indicating high variability in the WA in Tilga as per its seasonal hydrological patterns (Figure 4.29). The other two donor catchments, Gomlai and Jaraikela, maintained the lowest WA per km^2; however given their large catchment area (section 4.3.1.1), their monthly WA was large. The remaining recipient catchment Adityapur, displayed lower WA per km^2 during June-July; in the remaining months, Adityapur displayed better WA per km^2 than the main donor catchment Jaraikela. As expected, these results are in line with the hydrological patterns observed in catchments (section 4.4).

5.6.2 Water demand in the catchments

The findings suggest that, for 2050, the recipient basin displayed higher urban and industrial WD. The donor basin exceeded the recipient basin in rural, livestock and irrigation WD; differences for WD between the two basins were relatively small. Further, the research suggests that among all WD, environmental WD was relatively high in each of the catchments. Therefore, the environmental WD played an important role in estimating the total WD of the catchments. The donor basin displayed considerably higher environmental WD than the recipient basins; it surpassed recipient basin in total WD. Further, environmental WD was higher in monsoon months, which was reflected in the higher monthly WD during monsoon months. Overall, donor catchments displayed higher WD in monsoon months while recipient catchments showed higher WD during non-monsoon months. Furthermore, donor catchments displayed higher variability in the monthly WD as they have high irrigation and environmental WD in comparison to recipient catchments.

5.6.3 The surplus or deficit of water in the catchments

All catchments showed annual surplus water at 75% flow dependability for 2050. The recipient basin displayed higher water surplus than the donor basin despite its high domestic and industrial WD. It could be attributed to the environmental WD which is high in the donor basin leading to higher total WD in them. This influential role of environmental WD in total WD raises questions about the water-balance assessment carried out by the existing ILR planners that ignored the environmental requirement of rivers (NWDA 2009a; 2009b). The surplus water in Jaraikela, the main donor catchment, was only 20% greater from that observed in Adityapur, the main recipient catchment. The conditions of surplus water changed when catchments were examined at the monthly level. The donor catchments showed water deficit in the non-monsoon months which indicated that the donor catchments are water deficient within the annual cycle and need water for themselves. Therefore, water management interventions are required in donor catchments. The results thus suggest that donor catchment failed to qualify on the

IBWT criteria by Cox (1999) as they themselves struggle for their sustainability at their 75% flow dependability. On the other hand, although the recipient catchments remained surplus, the amount of surplus water was low and fell below 50 MCM during December-May. Therefore, the recipient catchments also indicated the need for water management interventions in managing their water.

5.7 Summary

The present chapter developed an integrated appraisal of WA and WD on an annual and monthly basis in the catchments of the two ILR projects, on the basis of which the research examined whether the donor and recipient catchments fulfilled the fundamental IBWT criteria by Cox (1999) or not. Under the integrated appraisal, the research assessed WA of each catchment at 75% dependability and WD of each catchment for the year 2050 on an annual and monthly basis. Using these WA and WD, the annual and monthly surplus or deficit of water in each catchment was estimated. Following are the major outcomes of the present research:

1. The annual natural WA at 75% dependability was higher in the donor basin. The donor basin displayed high WA in the monsoon months while the recipient basin showed high WA in the non-monsoon months. This seasonal distribution of WA in the study area indicates that recipient catchments are likely to have more WA in non-monsoon months than the donor catchments although the non-monsoon WA will remain low in both.
2. The recipient basin displayed higher urban and industrial WD while the donor basin displayed marginally higher rural, livestock and irrigation WD. The donor catchments displayed higher environmental WD. Further, the environmental WD played an important role in estimating the total WD of the catchments, given its higher volume among all WD considered. Thus, the total WD was higher in donor catchments. Furthermore, the donor catchments displayed higher total WD in monsoon months while recipient catchments showed higher total WD during non-monsoon months.
3. All catchments showed annual surplus water at 75% flow dependability. The recipient catchments showed higher surplus water than the donor

catchments. The monthly level of water surplus/deficit showed that the donor catchments were water deficit in the non-monsoon months. Although recipient catchments remained surplus during non-monsoon months, the amount of surplus water was very low.

Thereby, the present research suggests that although all catchments displayed surplus water at 75% flow dependability on an annual level, they struggle to meet their WD within the annual cycle due to the seasonal influence. Therefore, all catchments need water management interventions in order to ensure their sustainability. Nevertheless, this need is higher in the donor catchments. Thereby, the research found that the catchment failed to qualify on the IBWT criteria (Cox (1999) at their 75% flow dependability.

Chapter 6 Integrated modelling of inter-basin water transfer links: performance assessment

6.1 Introduction

As outlined in Chapter 2, this thesis develops a methodology for examining the decision-making of an Indian inter-basin Water transfer (IBWT) project, 'Inter-linking of Rivers' (ILR), based on published IBWT criteria (Cox 1999) using a rigorous scientific approach and the latest available data and tools in the public domain (Prabhu 2008; Bandyopadhyay 2012). This chapter addresses the fourth element of this thesis which assesses the performance of the two ILR links and their catchments in order to examine the risk and vulnerability of the ILR links and their donor and recipient catchments.

Existing research proposed that informed decision-making using the latest available data, tools, techniques and integrated approach should be used to explore potential projects (Bandyopadhyay 2012). Computer modelling is an important tool to contribute to such informed decision-making in water resource management (WRM) (Loucks 2008, Sechi & Sulis 2010) as it can efficiently assist in exploring the impact of various assumptions and policies (Loucks & Beek 2005). Globally, several IBWT projects have been examined using modelling, for instance: Beattie et al. (1971) (economic efficiency), Cai & McCarl (2007) (decision-making), Zhang et al. (2012) (stakeholders and conflicts), Yan et al. (2012) (water allocation and climate change), Gohari et al. (2013) (reliability), Li et al. (2014) (climate change and storage requirement), Li et al. (2015) (climate change and sustainable management), and Jia et al. (2015) (impact on ground water). However, ILR has only been simulated in a few studies. Jain et al. (2005) modelled ILR links and reservoirs of Godavari, Krishna, Pennar and Cauvery river basins using a generalised model 'Software for Reservoir Analysis (SRA)' (Jain & Goel 1996) and examined the performance reliability of the reservoirs under scenarios for without and with water IBWT projects. Gourdji et al. (2005, 2008) simulated the Himalayan component of ILR projects in the Ganges

River basin using Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) (US Army Corps of Engineers 2008) to generate flow at three different locations and examined change in them under pre- and post-diversion conditions of the ILR projects. Bharati et al. (2008) modelled the Polavaram ILR link (Godavari and Krishna river basins) using the Water Evaluation and Planning Model (WEAP) (Yates, Sieber, et al. 2005); the research assessed unmet water demand in the command area and some surrounding areas of the link. Although these studies examined ILR links, none of them covered the fundamental gap outlined by critics i.e. to examine the decision-making process followed in the ILR projects (sections 2.3-2.4). Jain et al. (2005) analysed water availability (WA) and water demand (WD) of only reservoirs instead of catchments, although they covered both donor and recipient basins. They checked the performance of reservoirs but did not explore the performance of ILR links themselves or of catchments in meeting their WD. Further, Gourdji et al. (2005, 2008) only addressed parts of the WA side and ignored the WD side completely.

Bharati et al. (2008) addressed both WA and WD but covered only the command area of the project and its surroundings; they ignored the rest of the donor and recipient catchments. Thus, the basic IBWT criteria (Cox 1999) were ignored by all existing studies. Moreover, none of the studies examined the performance of ILR links themselves and all the catchments involved (donor and recipients) (sections 2.3-2.4) which could indicate how well the ILR projects can function (Loucks & Beek 2005).

This research addresses this gap and simulates the two ILR links under study with their catchments in order to examine their performances in meeting their WD under conditions without and with ILR link conditions. This simulation will assist in exploring the annual or monthly risks and vulnerability of links and catchments, and in critiquing the existing ILR plans. The data, model and method used to fulfil this aim are explained in section 6.2. The simulation results demonstrating the performance of ILR links and catchments are given in section 6.3 and 6.4 and are discussed in section 6.5.

6.2 Materials

6.2.1 Study area

The study area has been explained in section 3.4.2 of Chapter 3 which specifies that the three out of six catchments being studied in this thesis, namely Tilga, Jaraikela and Adityapur, are divided into sub-catchments on the basis of offtake and outfall sites of the two ILR links, Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) (Figure 3.10). As discussed in Chapter 4, the two ILR links have been taken as one project on whose basis donor and recipient catchments have been defined (Figure 4.1).

6.2.2 Methodology

This research used the methodological framework developed on the basis of the best-practices in the IBWT field (Chapter 5) and the knowledge gained from the holistic and multi-disciplinary assessments of the catchments involved in both ILR projects (Chapter 4). Thus, the research undertook a sequence of tasks:

1. Selection of a suitable computer model,
2. The modelling of ILR links and their catchments,
3. Model run and results,
4. Performance assessment of the links and catchments.

Figure 6.1 present the flow chart of overall methodology used in the present study.

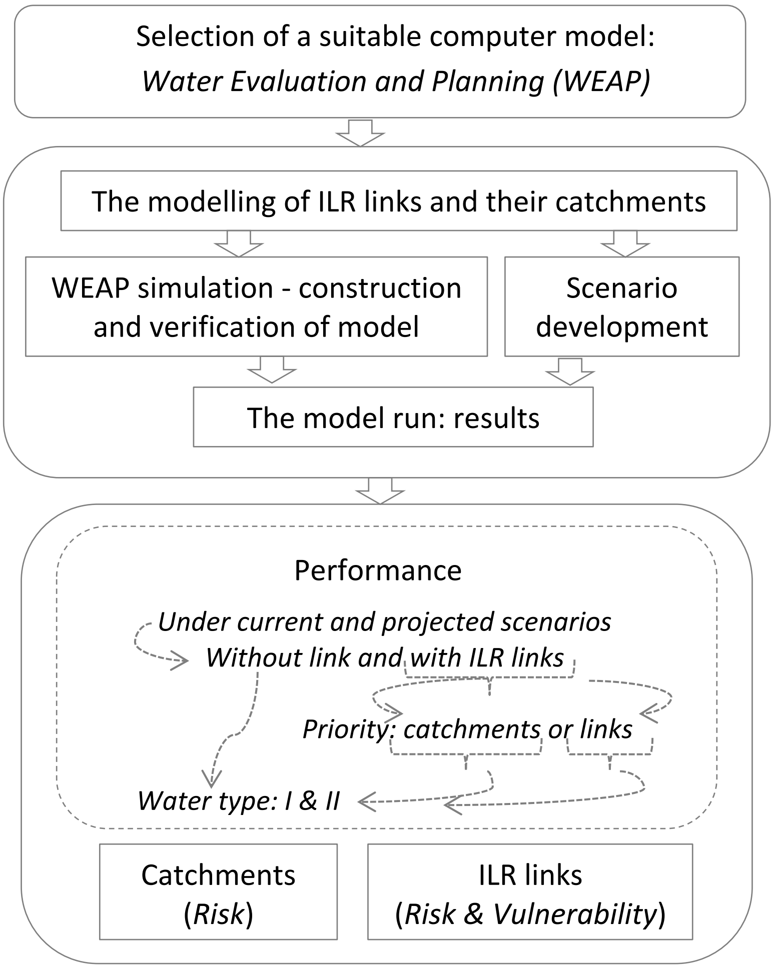


Figure 6.1: Flow chart of methodology used in simulation and then performance assessment of ILR links and their catchments.

6.2.2.1 Selection of a suitable computer model

A range of generic computer models designed for WRM were considered for the simulation. The fundamental criterion used in model-selection was the compatibility of the model with the methodological approach developed, but models were also examined on the criteria outlines in Table 6.1.

Table 6.1: Criteria used to select the model used in present study.

	Criteria	Rationale
1.	Integrated / System-based approach	To integrate management of WA and WD together.
2.	Spatial scale	To cover donor and recipient catchments of the two ILR links.
3.	Temporal scale	Can cover seasonal influence of monsoon.
4.	Potential to do scenarios	To assess several scenarios for WA & WD.
5.	Accommodate management and operational policies	To examine their impact on water transfer and catchments.
6.	Data requirements to function in robust way: parsimonious	To function efficiently with less data. The research uses data available in public domain and detailed data are generally unavailable in public.
7.	Key output (With priority in this research)	WA (3), WD (3), unmet WD (2), Reliability in meeting water demand (1).
8.	Cost (License)	Free as required by Dublin Principals (WMO 2017) or least cost.
9.	Least Training	For user's ease and to enhance the model usability
10.	User interface: graphic	User-friendly.

Models considered included: Soil Water Assessment Tool (SWAT) (Gassman et al. 2007), Aquatool (Andreu et al. 1996), MODSIM (Shafer 1979), Mike-SHE (Graham & Butts 2005), RIBASIM (Delft Hydraulics 2006), Water Rights Analysis Package (WRAP) (Wurbs et al. 1993) and Water Evaluation and Planning (WEAP) (Yates, Sieber, et al. 2005). Detailed comparison of these models are available in Loucks (2008), Koch & Grünewald (2009), Sechi & Sulis (2010), Droogers et al. (2011) and Sulis & Sechi (2013).

SWAT and Mike-SHE could not simulate WD without significant modification as required by the methodological approach used in this thesis and therefore were eliminated in the first round of model-selection. The remaining models considered were compatible with the methodological approach without significant customisation, so were examined for the criteria given in Table 6.1. They all fulfilled criteria 1-5; however, their suitability differed for criteria 6-10 (Table 6.2).

Table 6.2: Suitability of selected models for present research.

	Data Required (Low, Medium & High)	Key output (With priority in this research)	Cost (Free or to purchase)	Training need (Least, moderate, intensive)	User Interface: Graphic
Preference in present research	*Low*	*to higher priority*	*Free*	*Least*	*Yes*
Aquatool (UPV 2017)	High	WA	Limited version free otherwise cost associated[1];	Moderate	Yes
MODSIM (CSU 2017)	High	WA	Free	Moderate to Intensive	Yes
RIBASIM (DA 2017)	High	Reliability in meeting WD, WA	Free for research and education	Moderate	Yes
WRAP (TAMU 2015)	Medium	Reliability in meeting WD; WA	Free	Least	No
WEAP (SEI 2017)	Medium	Reliability in meeting water demand; unmet WD; WA; WD	Free for developing countries	Least	Yes

Suitability for present research	Low	Medium	High

Based on the overall suitability performance in all criteria, WEAP emerged as the most suitable generic model for the simulation required in the present research.

WEAP is used for planning and management of water resource (Yates et al. 2005). It was developed by the Stockholm Environment Institute, Boston (USA) and is based on an integrated approach (SEI 2017). It is simple, practical yet robust tool which can incorporate water supply and its demand along with its quality and associated ecological considerations within the region for integrated water resource planning and management (SEI 2017). It carries out integrated assessment of bio-physical and socio-economic factors which affect water resources in any given region (Yates et al. 2005). It puts issues related to WD (e.g. water-use, allocations, cost, strategies

[1] The main component of Aquatool is free however it needs separate components for the majority of tasks in which some are: 1. free for no-profit public institutions but no support; 2. Free for students and evaluation but reduced features and no support (UPV 2017)

etc.) on an equal basis with issues related to WA (e.g. flow, groundwater, water-transfer etc.) and facilitates an all-inclusive framework for planning and assessing water policies (SEI 2017). WEAP is highly flexible and user-friendly and can be applied at a range of spatial scales from municipalities to complex IBWT projects covering several river basins (Sieber & Prukey 2011). It can address wide-ranging concerns covering assessment of WD in different sectors, allocation of water as per priorities, simulation of river flow and/or groundwater, functioning of reservoirs, water-diversion, water conservation and hydroelectricity generation (Sieber & Prukey 2011). The financial analysis module of WEAP facilitates cost and benefit analyses of water projects (SEI 2017).

The WEAP model provides a system to maintain databases related to WA and WD (SEI 2017). It operates on the principles of water balance (Droogers et al. 2011) and follows a demand-, priority-, and preference-driven approach for simulation (Yates et al. 2005). It facilitates simulation of both natural (e.g. flow) and engineered units (e.g. water-diversion) of water systems (SEI 2017) and accommodates socio-economic conditions as well as management decisions influencing WA and WD (Sulis & Sechi 2013). WEAP simulation allows water managers to explore comprehensive scenarios accommodating a broad range of factors that must be considered during water resource management for current and future water-use (SEI 2017).

During WEAP simulation, various sources of water supply (e.g. river, reservoirs, groundwater, diversion etc.) and demand (e.g. population, agriculture, industry etc.) are represented as WEAP objects (Sieber & Prukey 2011). WA and WD is balanced in each of its nodes and links (WEAP-objects) in the modelled system (Sieber & Prukey 2011). The structure of the database can be customised as per the project-need and data-availability (SEI 2017). The model can accommodate data input in daily time-steps however it only provides results in monthly and annual time-steps (Sieber & Prukey 2011). A screen-shot of WEAP modelling schematic is shown in Figure 6.2.

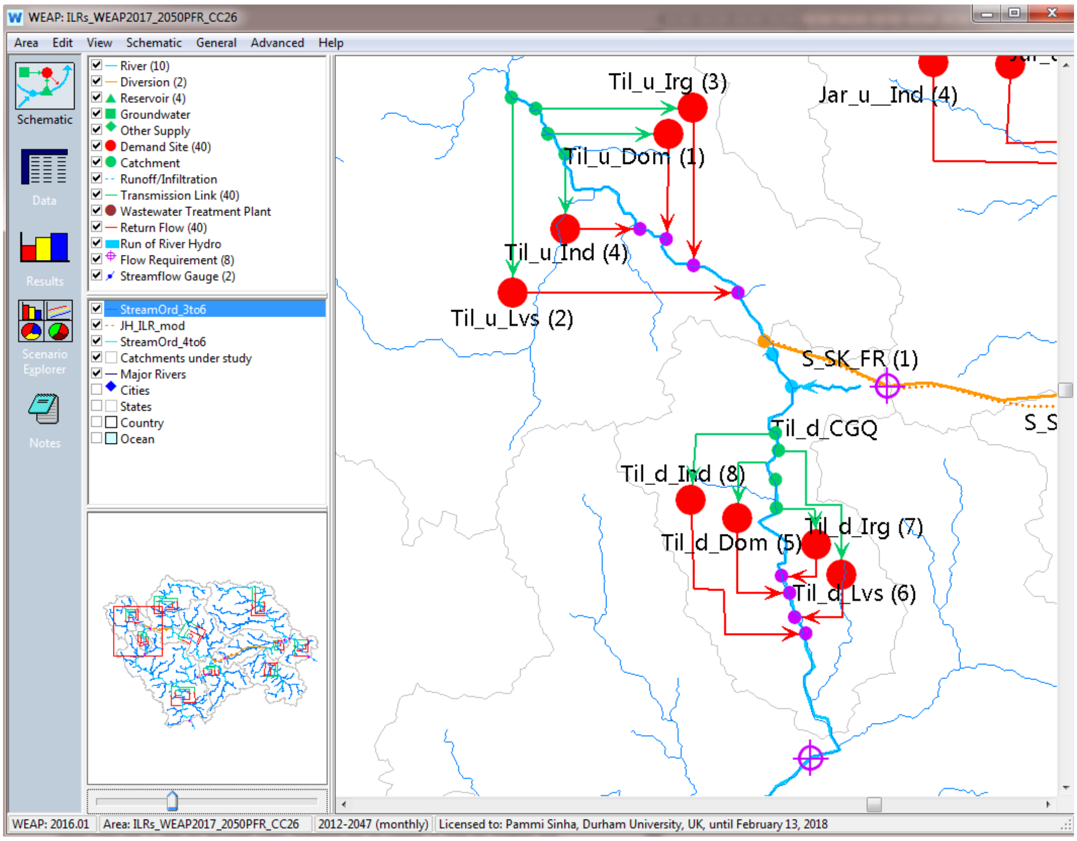


Figure 6.2: Screen-shot of WEAP modelling showing WA and WD WEAP-objects and demand priorities.

WEAP simulations generally include: study area definition, base scenario (current accounts), reference scenarios and evaluation of results (SEI 2017). WEAP allows comparative scenario-based analysis (Assata et al. 2008) which assists in examining the impact of changes in supply of water (such as climate change induced) and in the demand for water (such as management induced) based on projected demand and its reliability under various scenarios (Höllermann et al. 2010). Outputs from WEAP simulations include: WD, unmet WD, coverage, reliability (%), Instream flow reliability and WA at different nodes etc. (Sieber & Prukey 2011). It can be used for a range of studies such as: water allocation in different climate conditions (Lévite et al. 2003), water balance assessment under climate change (Rosenzweig et al. 2004), impact assessment of water and agricultural policies (Varela-Ortega et al. 2011), performance assessment of reservoirs (Swiech et al. 2012), finalising irrigation strategies (Mehta, Haden, et al. 2013); projection of WA and WD (Dimova et al. 2014) along with their associated costs (Mehta, Aslam, et al. 2013) and assessment of impacts due to water transfer projects (Bharati et al. 2008). A detailed description of WEAP is given in Yates et al. (2005), Yates & Purkey et al. (2005), Sieber & Prukey (2011) and SEI (2016).

6.2.2.2 The modelling of ILR links and their catchments

Before modelling the ILR links, the following assumptions were made:

i. Pre-feasibility studies by NWDA (2009a; 2009b) assumed 50% of rural WD and 100% of livestock WD would be fulfilled by ground water, yet livestock is one of the primary rural activities in the study area (section 4.5.2). Therefore, the present study:
   a. included livestock WD in the simulation.
   b. followed the rural WD pattern in order to meet its livestock WD from either surface or ground water.
ii. The growth rate of livestock population was assumed to be 1% per annum as advised by NWDA (2009a; 2009b).
iii. The growth rate of industrial WD was assumed to be 1% per annum because, first data related to industrial WD are rarely available in the public domain and second to avoid over-estimation.
iv. The permissible amount of groundwater which could be used in the study area amounts to only 4.9% of the total WA available in the study area (section 4.3- Table 4.5). Therefore, it was not included directly in the simulation. In only one instance, to examine the assumption case of NWDA (2009a; 2009b), 50% of rural and livestock WD was assumed to be fulfilled by groundwater and its return flow was assumed to be returned to the ground water itself.

The modelling of ILR links and catchment involved two steps which are:

i) WEAP simulation - construction and verification of model, and
ii) Scenario development.

i) WEAP simulation - construction and verification of model

First of all, a schematic was created in WEAP to simulate ILR links and their catchments (Figure 6.3).

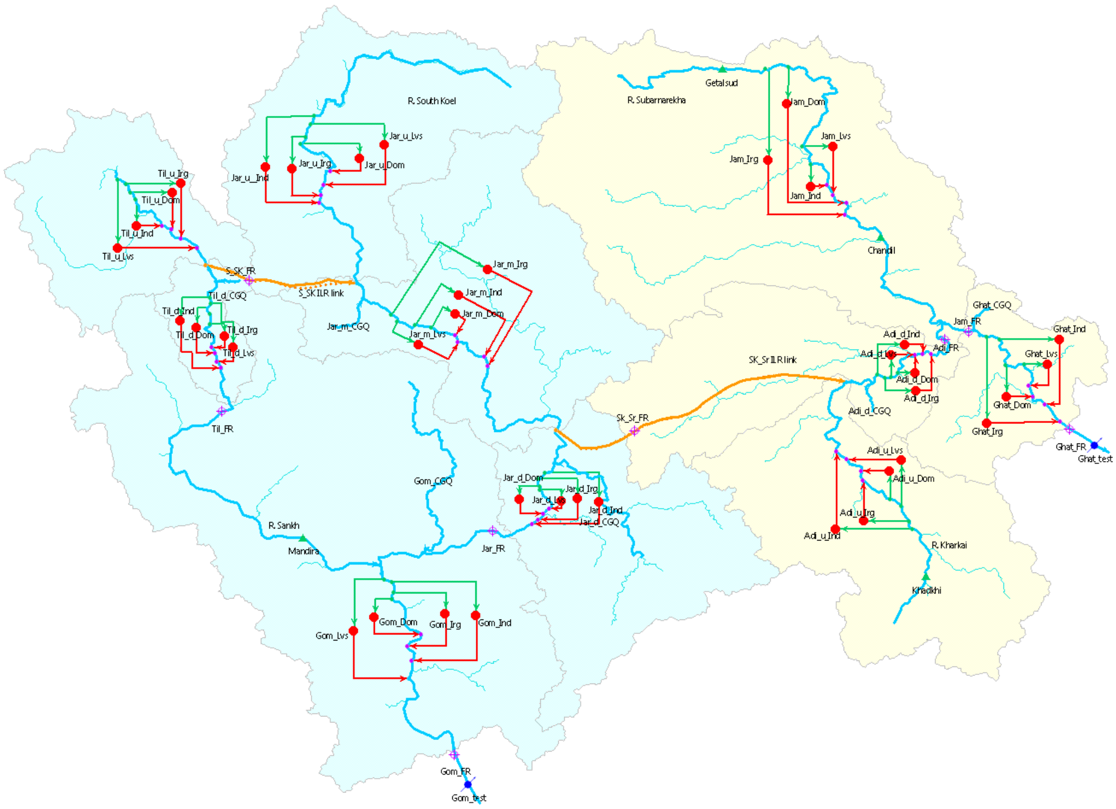


Figure 6.3: Schematic of integrated simuation of ILR links and their catchments in WEAP.

To create this schematic, GIS layers for rivers, catchment boundaries and ILR links were used as the base data. WEAP objects for main rivers and representative tributaries[2] were added in the model to simulate the WA and all supply sources were given the same preference. To simulate the WD, demand nodes for different sectors (domestic including urban and rural, livestock, irrigation and industry), transmission links, return flows, and water diversion links were created. High priority was given to domestic WD followed by livestock irrigation and then industry. All WD in the upstream catchments were prioritised over WD in the downstream catchments. WEAP objects for minimum flow requirements

[2] For each catchment, only one tributary was added representing all tributary rivers in the catchment accounting for flow generated in the catchment.

(representing environmental WD) and streamflow gauges (for model validation using observed flow) were also added in the model. Minimum flow requirements were also given high priority (similar to the domestic WD). After creating the schematic, data were entered in the different components of the model.

1. Water availability (WA)

To simulate WA of catchments, naturalised flows for all six HOC (1980-2013) were calculated as:

Naturalised flow = Observed flow + Net water demand + Reservoir storage

Here it should be noted that based on NWDA (2009a; 2009b) and India-WRIS (2012):

a. Net WD = Gross WD – regeneration. The regenerated flows from the domestic, livestock and industrial WD are taken as 80% each. The regenerated flow from the irrigation WD is taken as 10%.
b. There is currently no import or export of water from or to the catchments.
c. The data for irrigation WD and reservoirs included evaporation from them.
d. Reservoirs above 1 MCM were included.

After calculating naturalised flow for each of the six catchments, the naturalised flows for the sub-catchments of the Tilga, Jaraikela and Adityapur catchments were calculated on the basis of their area-ratio with their respective catchments. These natural flows were used as a water supply in each of the catchments or sub-catchments via either the main rivers (Sankh, South Koel, Kharkai and Subarnarekha) or tributaries. The two ILR links (S-SK and SK-Sr) were simulated using the proposed monthly water-transfer amount (MCM) given by NWDA (2009a; NWDA 2009b).

2. Water demand (WD)

For each demand node (domestic including urban and rural, livestock, irrigation and industry), annual activity, water-use rates, consumption percentage and monthly variation were used. Monthly variation was evident in only irrigation; for the domestic, livestock and industry WD showed no significant monthly variation. Further, minimum flow requirement thresholds, based on Smakhtin & Anputhas (2006), were used for the environmental WD. Following Smakhtin & Anputhas (2006), rivers in Brahmani and Subarnarekha basins were taken as 'moderately modified' (class C) and 'largely modified' (class D) respectively; their respective flows at 99% and 95% dependability were therefore used as their minimum flow requirements.

After setting up the model, streamflow gauges at the two final outflow points, Gomlai HOC for the donor basin and Ghatshila HOC for the recipient basin (Figure 6.3), were used for the model verification as advised by Krause & Boyle (2005). Visual comparison as well as the Nash-Sutcliffe efficiency (*E*) (Nash & Sutcliffe 1970) and coefficient of determination (r^2) were calculated (details in Krause & Boyle 2005) to evaluate the results obtained.

ii) Scenario development

Scenarios are useful to account for the uncertainties associated with factors affecting WRM (e.g. climate, socio-economic and policies) in current and future time-periods (Dong et al. 2013). Scenarios can be grouped into three: predictive (to forecast), explorative (to understand the consequences) and normative (to reach specific target) (Börjeson et al. 2006) with 'explorative scenarios' often being the most helpful in informed decision-making (Haasnoot & Middelkoop 2012). Therefore, the present research developed a range of explorative scenarios which involved a range of factors which are given in Table 6.3. In order to keep track of the scenarios developed, the factors have been coded (given in adjoining brackets).

Table 6.3: Sets and subsets of factos used to develop scenarios for the simulation of the ILR links and their catchments

Factors	Reasons
Time-period	
Current (2012)	Depicting current or base situations (2012).
Probable future with change in water demand (2050-WD)	Depicting change in demand drivers (socio-economic) in projected future.
Projected future with changes in WD and climate (2050-WD-CC)	Depicting change in demand drivers (socio-economic) and climate in the projected future in order to check if climate change (CC) has any bearing on WA in the catchments. The assessment for CC influence was of basic level and was based on the work by Chaturvedi et al. (2012). Chaturvedi et al. (2012) projected precipitation in India during 2021-2099 using four 'Representative Concentration Pathways (RCPs)' under the Coupled Model Inter-comparison Project 5 (CMIP5). Their outputs (0.5°x0.5°) for maximum precipitation change (%) under two of the RCPs, namely RCP - 2.6 (with lowest greenhouse gas emission by 2100 among the four RCPs) and RCP – 8.5 (with highest greenhouse gas emission by 2100 among the four RCPs) were used in the present study (Details of RCPs in Wayne 2013) to project the flow in 2050 at the catchments under study. Rainfall-flow relationship within the catchments which was derived from the hydrological analysis of the study area (chapter-4, section 4.4.3 and Figure 4.37) was used in flow projection.
Influence of links	
Without ILR link (WoL)	To assess 'business as usual (BAU)' scenarios in which ILR links are not functioning.
With ILR link (WL)	To assist in examining: 1) the 'what-if' situations in the catchments when ILR links are operated and; 2) the risk and vulnerability of ILR links itself.
In case of water transfer, priority given to:	
catchment's requirement (PC)	To assess situations when WD within catchments is given higher priority over water transfer.
ILR links (PL)	To assess situations when water transfer is given higher priority over catchments' WD.
Type of water source to fulfil rural and livestock water demands:	
Water type I (WT I)	To assess the impact of water management policy when 50% of rural and livestock WD are fulfilled by ground water.
Water type II (WT II)	To assess the impact of water management policy when all rural and livestock WD are fulfilled by surface water.

Using the factors from Table 6.3, simulation scenarios were developed at two levels: primary and secondary (Figure 6.4). Primary-level scenarios included base scenarios and probable future scenarios (socio-economic and climate change) based on the factor ‘time period’.

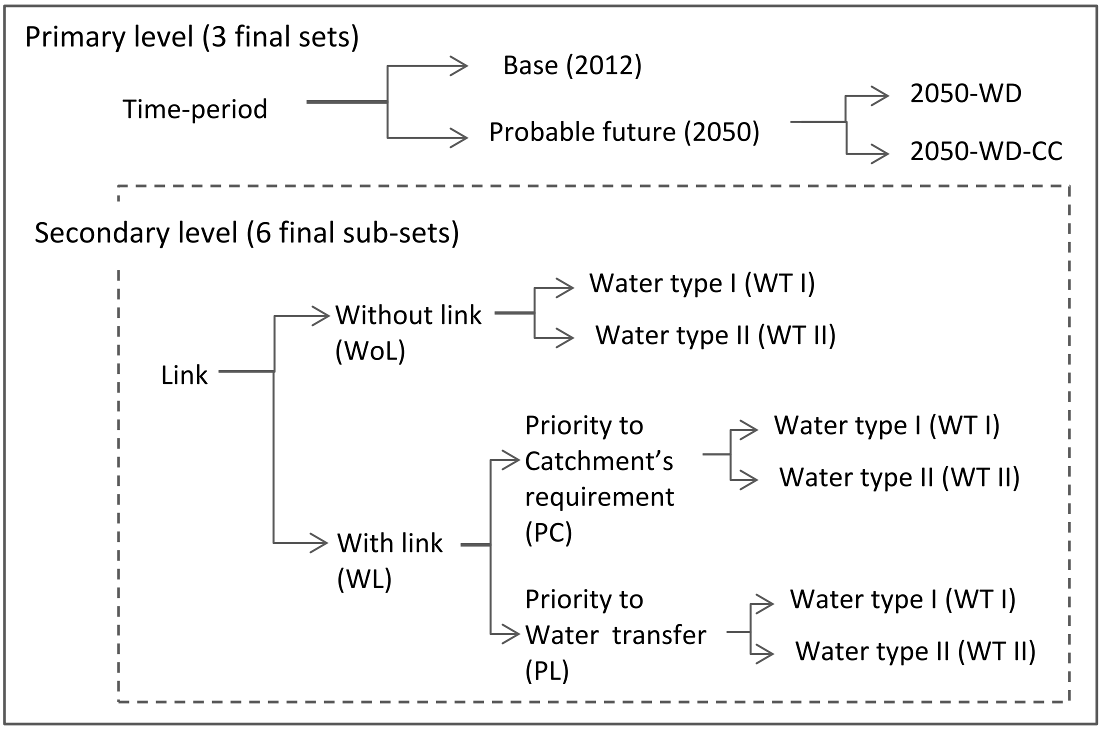


Figure 6.4: The scenario development along its primary and secondary levels

For each of the three primary levels, six secondary-level scenarios were developed using the remaining subsets of factors (Figure 6.4). In total 3 primary sets and 6 subsidiary sets of scenarios were developed for the simulation (Table 6.4).

Table 6.4: Sets and sub-sets of scenarios deveoped in present research

Current scenarios	Probable future scenarios (2050) with change in	
(2012)	Water demand	Water demand & climate change
2012-WoL-WT I	2050-WD-WoL-WT I	2050-WD-CC-WoL-WT I
2012-WoL-WT II	2050-WD-WoL-WT II	2050-WD-CC-WoL-WT II
2012-WL-PC-WT I	2050-WD-WL-PC-WT I	2050-WD-CC-WL-PC-WT I
2012-WL-PC-WT II	2050-WD-WL-PC-WT II	2050-WD-CC-WL-PC-WT II
2012-WL-PL-WT I	2050-WD-WL-PL-WT I	2050-WD-CC-WL-PL-WT I
2012-WL-PL-WT II	2050-WD-WL-PL-WT II	2050-WD-CC-WL-PL-WT II

The first two sets of scenarios for each time-period represented the conditions for without ILR links i.e. business-as-usual (BAU) conditions. They included two types of water sources (Table 6.3). The further four sets of scenarios for each time-period represented the conditions for with ILR links i.e. scenarios with functioning water transfer projects. The first two scenarios are for the conditions when priority is given to the WD within the catchments and the final two scenarios are for the conditions when priority is given to the water transfer by ILR links. Similar to BAU scenarios, each of the four scenarios of functioning water-transfer are further divided into two on the basis of two types of water sources (Table 6.3).

6.2.2.3 The model run: results and their assessment

After the scenario development, the model was run for each scenario and several model outputs at annual and monthly scales were generated. Major model outputs used in the present study are: reliability (in meeting WD by catchment and ILR links) and unmet WD. These outputs were used directly and indirectly as performance indices to check the performance of ILR links and their catchments at annual and monthly time scales. The first performance index used is based on the reliability index (Hasimoto 1982), the most commonly-used index to check the performance of any water resource system (Mujumdar 2011). Reliability was used by Jain et al. (2005) and Gohari et al. (2013) while examining the impact of IBWT. It shows the probability (%) of WD to be met completely by the available water resources (Gohari et al. 2013). The opposite of reliability is '*risk*' (Hasimoto 1982) which has been used in the present research in order to represent the results efficiently.

Annual reliability of ILR links and catchment was directly produced by WEAP, while monthly reliability was calculated using monthly unmet WD for each month. Both were based on Hasimoto (1982).

$$\text{Reliability (\%) (annual and monthly)} = \frac{\text{Number of time-periods WD was fulfilled}}{\text{Total number of time-periods considered}} \times 100\%$$

$$\therefore \quad \text{Risk (\%)} = 100 - \text{Reliability \%}$$

The risk is categorised as low (0-25%), moderate (25-50%), significant (50-75%) and highly significant (75-100%).

Further, in order to understand the overall exposure of ILR links and to explore their likely extent of failure at the annual and monthly scale, another performance index 'Vulnerability' (Hasimoto 1982) was considered. This index has also been used by Gohari et al. (2013) in examining the impact of IBWT. As suggested by Loucks & Beek (2005) and Sandoval-Solis et al. (2011), vulnerability of ILR links (expressed as %) was calculated as follows:

$$\text{Vulnerability (\%) (Annual and monthly)} = \frac{\text{Average unmet WD by the ILR links to satisfy the proposed water transfer (NWDA 2009a; NWDA 2009b)'}}{\text{WD by the ILR links to satisfy the proposed water transfer (NWDA 2009a; NWDA 2009b)}} \times 100\%$$

Finally, these results were assessed to explore the performances of ILR links and their catchments. In order to break down the results the following arrangement is offered:

1) Catchments: Risks
    a) Risks during current scenario:
        i) in meeting WD of the catchments,
            (1) without ILR links (i.e. during BAU),
            (2) with ILR links (i.e. during water transfer),
                (a) Priority given to the WD within the catchments (PC),
                (b) Priority given to the water transfer by ILR links (PL),
        ii) in meeting flow requirements of the catchments.

b) Risk during probable future scenarios with only WD changes:

i) in meeting WD of the catchments,

(1) without ILR links (i.e. during BAU),

(2) with ILR links (i.e. during water transfer),

(a) Priority given to the WD within the catchments (PC),

(b) Priority given to the water transfer by ILR links (PL),

ii) in meeting flow requirement of the catchments.

c) Influence of climate change on the risks for catchments during probable future scenarios,

i) in meeting WD of the catchments,

ii) in meeting flow requirements of catchments.

2) The ILR links: Risks and vulnerability

a) Risks in meeting the proposed flow by the ILR links:

i) during current scenarios,

(1) Sankh-South Koel (S-SK) ILR link,

(2) South Koel-Subarnarekha (SK-Sr) ILR link,

ii) during future scenarios,

(1) Sankh-South Koel (S-SK) ILR link,

(2) South Koel-Subarnarekha (SK-Sr) ILR link.

iii) Influence of climate change on the risks for ILR links during probable future scenarios.

b) Vulnerability in ILR links:

i) during current scenarios,

(1) Sankh-South Koel (S-SK) ILR link,

(2) South Koel-Subarnarekha (SK-Sr) ILR link,

ii) during future scenarios,

(1) Sankh-South Koel (S-SK) ILR link,

(2) South Koel-Subarnarekha (SK-Sr) ILR link.

6.3 Catchments: Risks

Simulation of ILR links and catchments (Figure 6.3) was verified using simulated flow and observed flow at Gomlai and Ghatshila HOCs (Figure 6.5). Both the Nash-Sutcliffe efficiency (*E*) and the coefficient of determination showed high confidence in the model. For Gomlai, *E* was 0.97 and r^2 was 0.99 while for Ghatshila, *E* was 0.86 and r^2 was 0.95. Thus model results could be used confidently for assessing the performance of the ILR links and catchments.

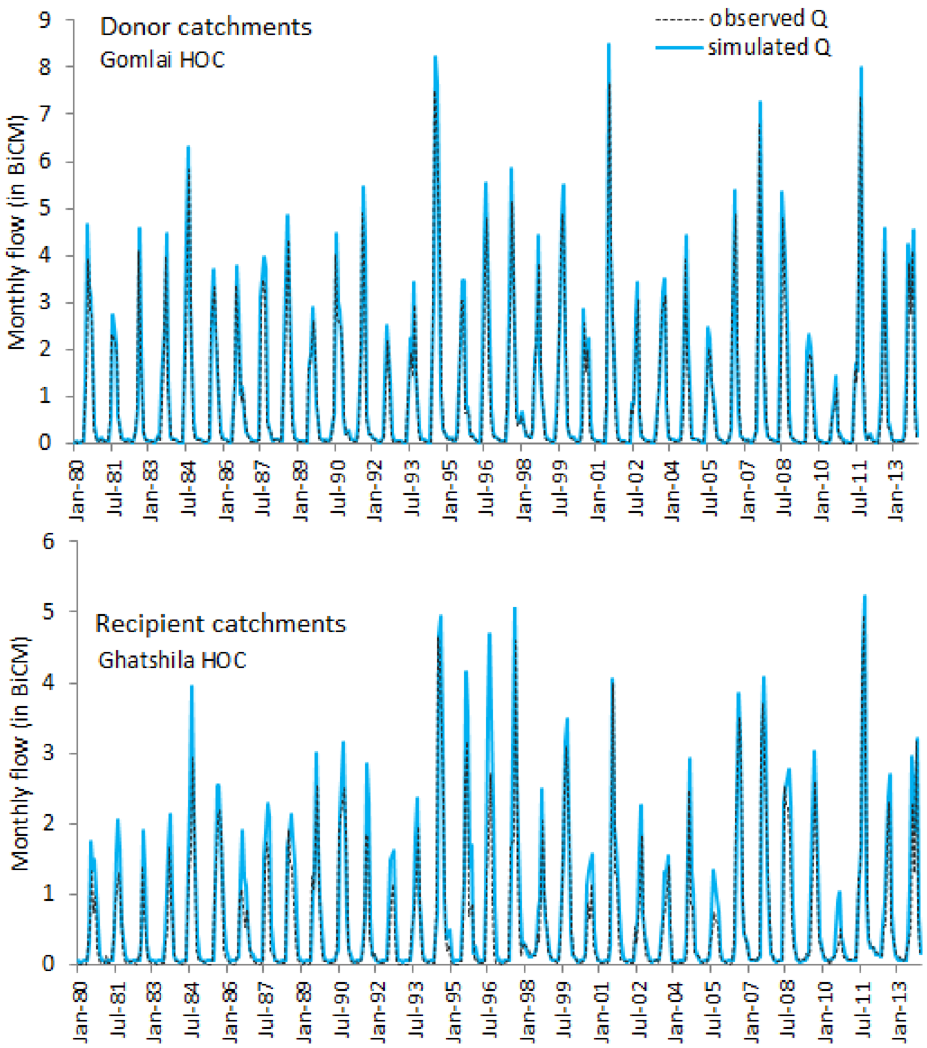


Figure 6.5: Observed and simulated flow at the two Hydrological Observation Centres (HOC) situated at the final outflow points: Gomlai (for donor catchments) and Ghatshila (for reciepient catchments).

Annual and monthly risks observed in each catchment are grouped into two major sets: 'without ILR links' i.e. business as usual (BAU) scenarios and 'with ILR link' i.e. water-transfer scenarios and are explained for current (2012) and future scenarios (2050) covering future risks due to change in WD (2050-WD) as well the potential influence of climate change on the risks observed during 2050-WD (i.e. 2050-WD-CC).

6.3.1 Risks during current scenario

6.3.1.1 In meeting WD of the catchments

The risks observed in meeting WD of the catchment in the current period (2012) covered BAU and water transfer i.e. scenarios (Table 6.5- Table 6.10).

i) Without ILR links (i.e. during BAU) (2012-WoL)

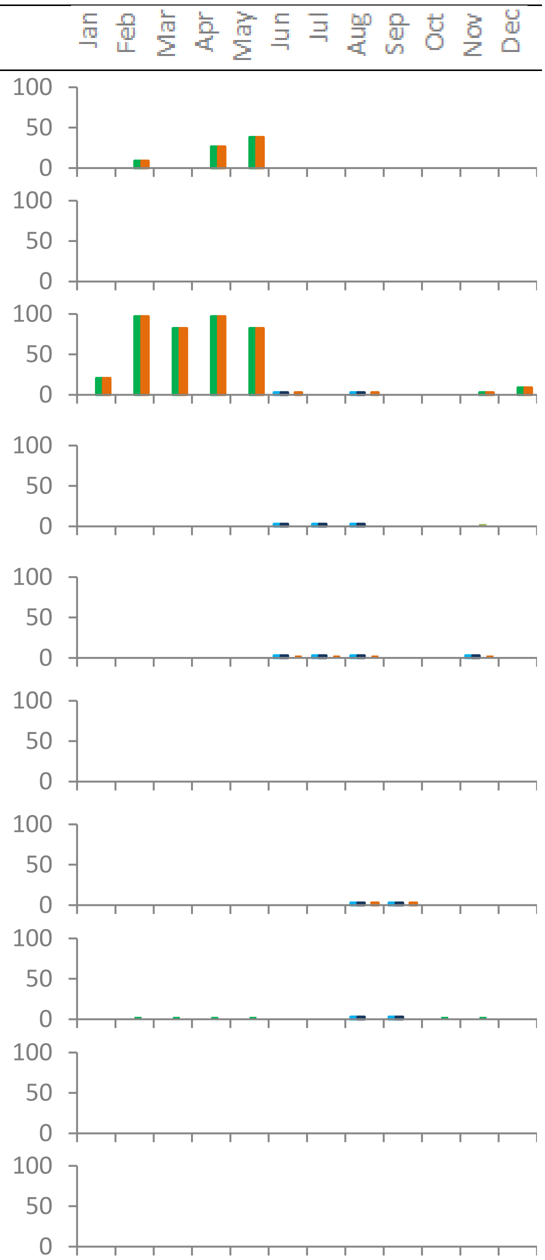
The set of BAU scenarios (2012-WoL) for risks in meeting WD covered two subsets (Table 6.5-Table 6.6), based on the water type (WT I and WT II) (Table 6.3). It was noted that among donor catchments, upstream of Tilga showed minor annual risks in fulfilling irrigation and industrial WD with low to moderate monthly risks during April-May. Upstream of Jaraikela showed moderate annual risk in meeting irrigation and industrial WD which demonstrated significantly higher risks during February-May although insignificant risks were visible during some other months including monsoon months. The rest of the catchments and sub-catchments in the donor basin showed negligible or no risk in meeting their WD. The two sub-catchments of Adityapur in the recipient basin showed insignificant risks in all WD which were evident in August-September. The rest of the two recipient catchments exhibited no risk in meeting their WD.

It was observed that the risks differed marginally in the scenarios for the two water types (WT I and WT II) and exceeded slightly in the WT II scenario, albeit the increase was negligible (Table 6.6).

Table 6.5: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in current scenario, without ILR links and with water type I (2012-WoL-WT-I)

		Annual risk (%)			
		Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	0	0	5.8	5.8
	Downstream: below S-SK link's start	0	0	-	-
Jaraikela	Upstream: above S-SK link's fall	0.5	0.5	32.9	33.3
	Middle: below of S-SK link's fall & above SK-Sr link's start	0.7	0.7	0.2	-
	Downstream: below of SK-Sr link's start	0.9	0.9	-	0.9
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0.5	0.5	0	0.5
	Downstream: below of SK-Sr link's fall	0.5	0.5	1.4	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%) | 0-25 (%) | 25-50 (%) | 50-75 (%) | 75-100 (%) | Water use: Domestic, Livestock, Irrigation, Industry

Significance | Low | moderate | high | Very high

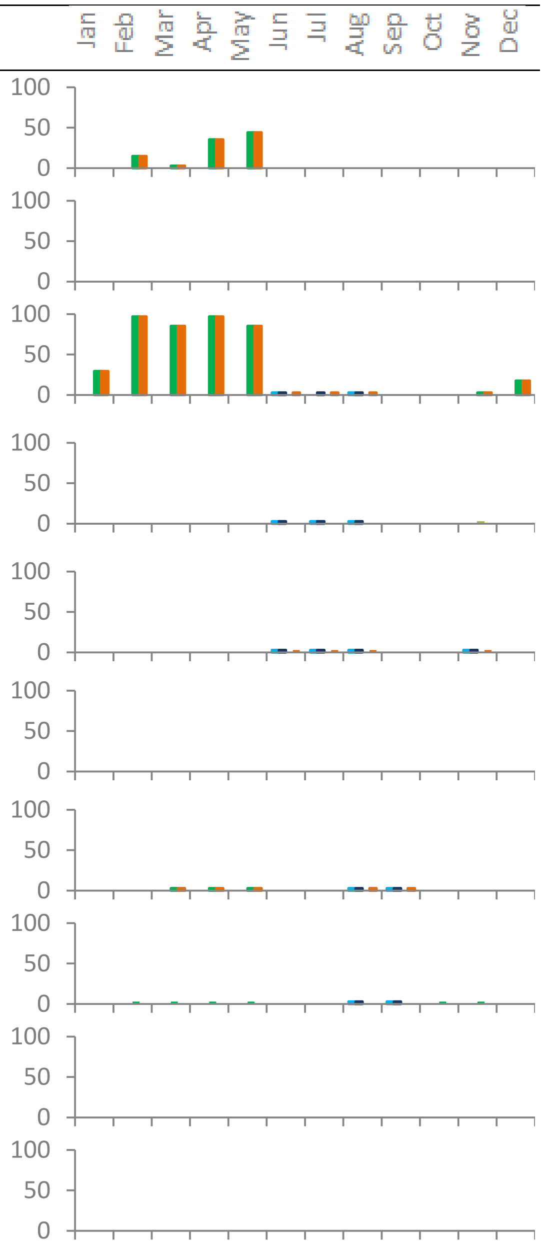
Note: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

Table 6.6: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in current scenario, without ILR links and with water type II (2012-WoL-WT-II)

		Annual risk (%)			
		Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	0	0	7.6	7.6
	Downstream: below of S-SK link's start	0	0	-	-
Jaraikela	Upstream: above S-SK link's fall	0.5	0.7	34.7	35.4
	Middle: below of S-SK link's fall & above SK-Sr link's start	0.7	0.7	0.2	-
	Downstream: below of SK-Sr link's start	0.9	0.9	-	0.9
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0.5	0.5	0.7	1.2
	Downstream: below of SK-Sr link's fall	0.5	0.5	1.4	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%)	0-25 (%)	25-50 (%)	50-75 (%)	75-100 (%)
Significance	Low	moderate	high	Very high

Water use: Domestic, Livestock, Irrigation, Industry

Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

ii) With ILR links (i.e. during water transfer) (2012-WL)

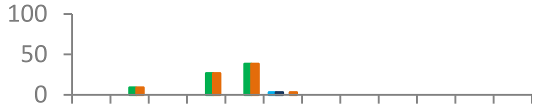
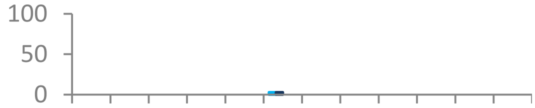
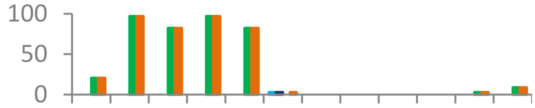
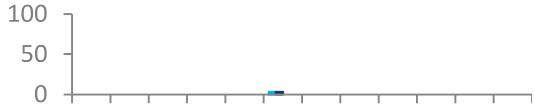
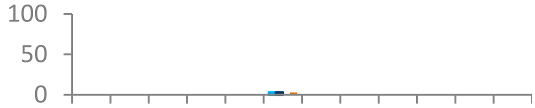
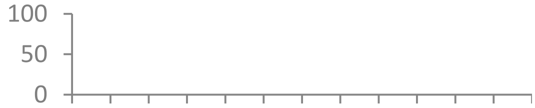
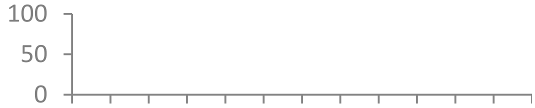
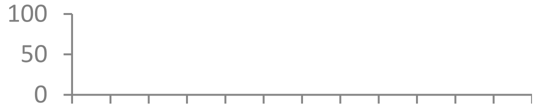
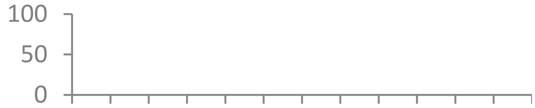
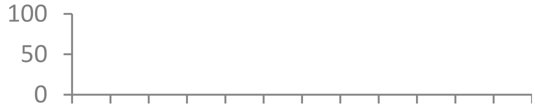
Water-transfer scenarios (Table 6.7-Table 6.10) were grouped on the basis of priority: 'priority to catchment (2012-WL-PC)' and 'priority to ILR links (2012-WL-PL)'. Each of these was further grouped by water types, WT I and WT II.

a) Priority given to the WD within the catchments (PC)

The annual and monthly risks in these catchments prioritised water-transfer scenarios (2012-WL-PC) and are given in Table 6.7 and Table 6.8 respectively. It was noted that among donor catchments, both sub-catchments of Tilga showed a marginal increase in all WD due to water transfer (Table 6.5-Table 6.8). Their monthly pattern revealed intensified risks during February-May in the upstream of Tilga catchment; however, the downstream Tilga showed only minor risks in June. In Jaraikela, all sub-catchments demonstrated marginally improved conditions in all risks however moderate annual risk in meeting irrigation and industrial WD was still visible in the upstream Jaraikela. Monthly risk seen in upstream Jaraikela revealed similar patterns as seen in BAU scenarios with negligible variations in them. Middle and downstream Jaraikela showed an improved monthly risk pattern with risk visible only in June. The remaining donor catchment, Gomlai, showed no risk. In the recipient basin, sub-catchments of Adityapur which showed minor risks during BAU scenarios, demonstrated no risk after water transfer. The other two recipient catchments, Jamshedpur and Ghatshila showed no risk in meeting their WD.

Further, similar to BAU scenarios, water types showed a negligible increase when WT II was considered; however, the overall influence remained insignificant.

Table 6.7: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in current scenario, with ILR links (priority catchments) and with water type I (2012-WL-PC-WT-I)

		Annual risk (%)				Monthly risk (%)
		Domestic	Livestock	Irrigation	Industry	Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Tilga	Upstream: above S-SK link's start	0.2	0.2	5.8	6	
	Downstream: below S-SK link's start	0.2	0.2	-	-	
Jaraikela	Upstream: above S-SK link's fall	0.2	0.2	32.9	33.1	
	Middle: below S-SK link's fall & above SK-Sr link's start	0.2	0.2	0	-	
	Downstream: below SK-Sr link's start	0.2	0.2	-	0.2	
Gomlai		0	0	0	0	
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0	
	Downstream: below SK-Sr link's fall	0	0	0	*-	
Jamshedpur		0	0	0	0	
Ghatshila		0	0	0	0	

Risk (%)	0-25 (%)	25-50 (%)	50-75 (%)	75-100 (%)	Water use	Domestic, Livestock, Irrigation, Industry
Significance	Low	moderate	high	Very high		

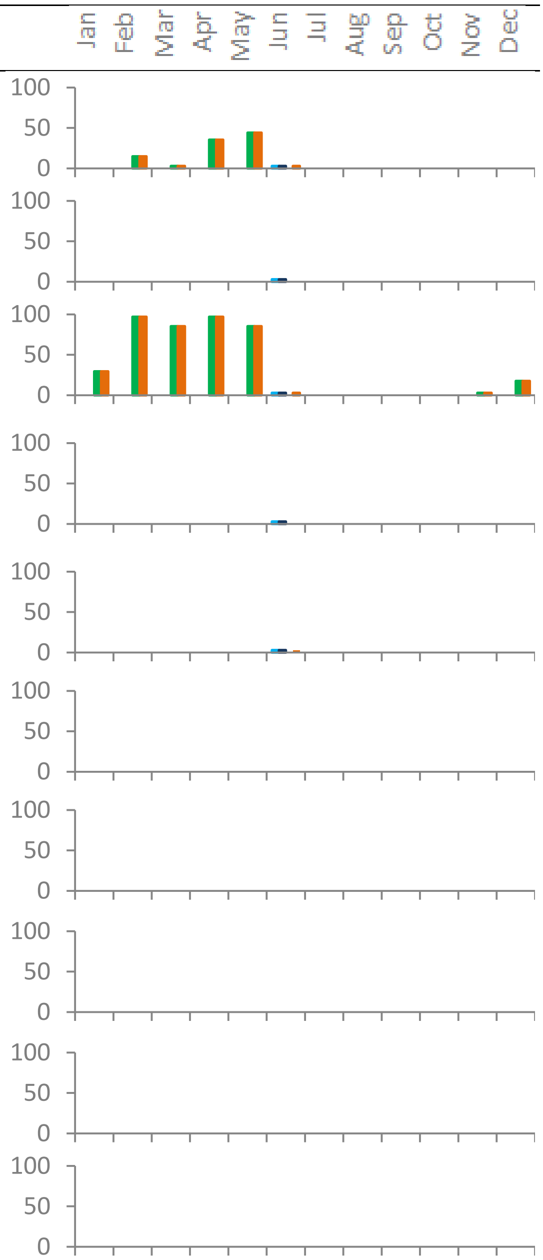
Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

Table 6.8: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in the current scenario, with ILR links (priority catchments) and with water type II (2012-WL-PC-WT-II)

		Annual risk (%)			
		Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	0.2	0.2	7.6	7.9
	Downstream: below S-SK link's start	0.2	0.2	-	-
Jaraikela	Upstream: above S-SK link's fall	0.2	0.2	34.7	35
	Middle: below S-SK link's fall & above SK-Sr link's start	0.2	0.2	0	-
	Downstream: below SK-Sr link's start	0.2	0.2	-	0.2
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0
	Downstream: below SK-Sr link's fall	0	0	0	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%)	0-25 (%)	25-50 (%)	50-75 (%)	75-100 (%)
Significance	Low	moderate	high	Very high

Water use: Domestic, Livestock, Irrigation, Industry

Notes: - No water demand thus no risk.
*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

b) Priority given to the water transfer by ILR links (PL)

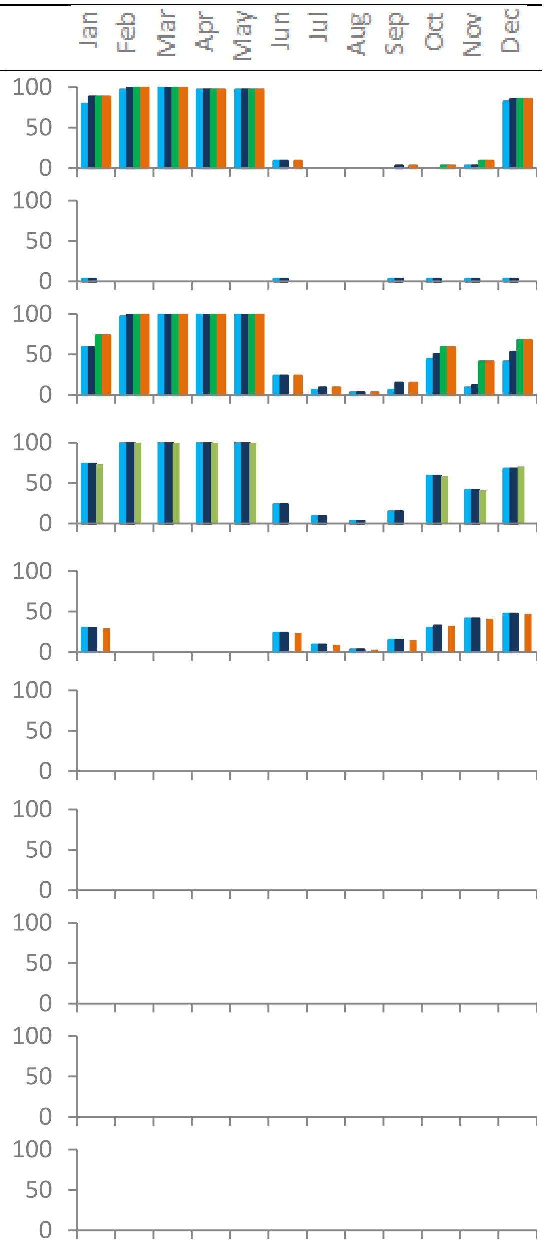
The annual and monthly risks in these links prioritised water-transfer scenarios (2012-WL-PL) given in Table 6.9 (for WT I) and Table 6.10 (WT II) respectively. These scenarios showed a remarkable increase in risks when water transfer was prioritised over WD in catchments.

Among donor catchments, upstream of Tilga showed a sharp increase in risk for all WD in comparison to previous scenarios (Table 6.5-Table 6.8) and the sub-catchment faced moderate risk in both of these scenarios (Table 6.9-Table 6.10). Downstream Tilga also showed a minor increase in the risk of all four of its WD although it was insignificant. The catchment exhibited high risk during most of the non-monsoon months and showed 100% risk during February-May. Further, the sub-catchments of Jaraikela displayed heightened risks in all WD which were largely significant for its upstream and middle sub-catchments. The pattern of monthly risk in Jaraikela was more intense than that of Tilga. In the upstream and middle Jaraikela sub-catchments, all months displayed substantial risk ranging from highly (in non-monsoon months), to moderately (in monsoon months) significant with 100% risk during February-May. Downstream Jaraikela exhibited low to moderate risk during June-January and displayed no risk during February-May. The rest of the catchments and sub-catchments in the donor and recipient basins showed no risk in meeting their WD. As with the other scenarios, water types showed insignificant influence on the annual and monthly risks.

Table 6.9: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in current scenario, with ILR links (priority links) and with water type I (2012-WL-PL-WT-I)

Catchment	Location	Annual risk (%) Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	45.6	47.2	47	47.9
	Downstream: below S-SK link's start	1.4	1.4	-	-
Jaraikela	Upstream: above S-SK link's fall	47.9	50.7	52.5	56.9
	Middle: below S-SK link's fall & above SK-Sr link's start	56	56	51.9	-
	Downstream: below SK-Sr link's start	16.2	16.4	-	16.4
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0
	Downstream: below SK-Sr link's fall	0	0	0	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%): 0-25 (%) | 25-50 (%) | 50-75 (%) | 75-100 (%)
Significance: Low | moderate | high | Very high

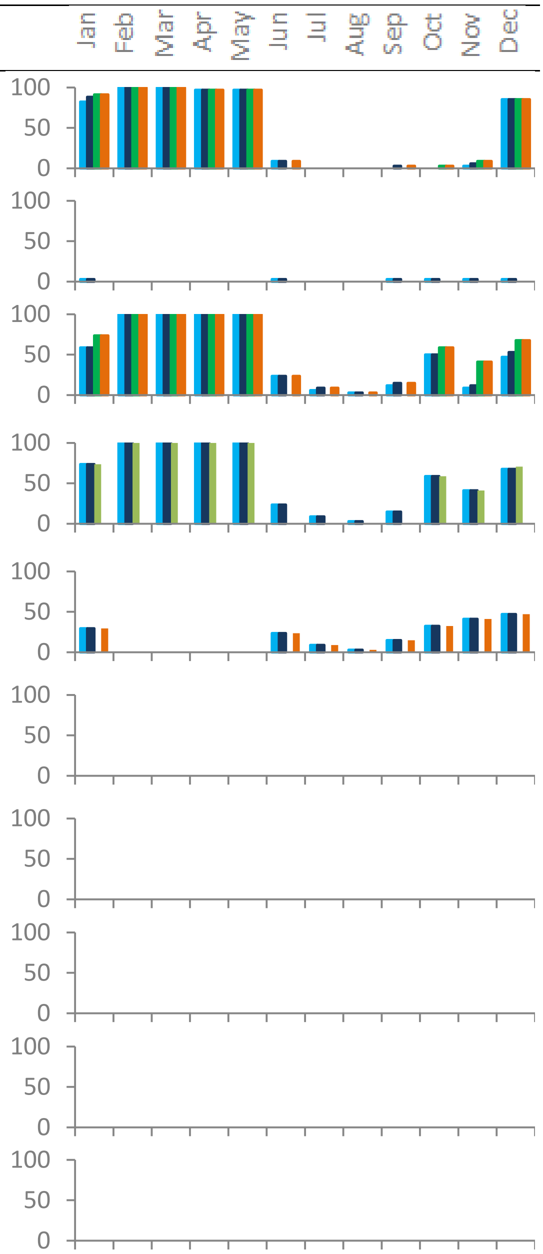
Water use: Domestic, Livestock, Irrigation, Industry

Notes: - No water demand thus no risk.
*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

Table 6.10: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in current scenario, with ILR links (priority links) and with water type II (2012-WL-PL-WT-II)

		Annual risk (%)			
		Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	46.5	47.5	47.2	48.1
	Downstream: below S-SK link's start	1.4	1.4	-	-
Jaraikela	Upstream: above S-SK link's fall	49.5	50.7	52.5	56.9
	Middle: below S-SK link's fall & above SK-Sr link's start	56	56	51.9	-
	Downstream: below SK-Sr link's start	16.2	16.4	-	16.4
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0
	Downstream: below SK-Sr link's fall	0	0	0	*-
Jamsh edpur		0	0	0	0
Ghats hila		0	0	0	0

Monthly risk (%)



Risk (%) 0-25 (%) 25-50 (%) 50-75 (%) 75-100 (%) Water use Domestic Livestock Irrigation Industry

Significance Low moderate high Very high

Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

6.3.1.2 In meeting flow requirements of the catchments

The catchments were largely able to fulfil their flow requirement (environmental WD) in BAU as well as water-transfer scenarios during the current time-period (Table 6.11-Figure 6.6).

Table 6.11: Current scenarios (2012): Risks in meeting: (a) flow requirement (environmental WD) at catchments (measured at their HOCs), and (b) proposed monthly water transfer by the two ILR links (Source: NWDA 2009a; NWDA 2009b)

Hydrological Observation Centre (HOC) of each catchment	Risk in meeting required flow (2012)					
	Without ILR link		With ILR link			
	WT I	WT II	Priority catchments		Priority ILR links	
			WT I	WT II	WT I	WT II
Scenarios: 2012-	*WoL-WTI*	*WoL-WTII*	*WL-PC-WTI*	*WL-PC-WTII*	*WL-PL-WTI*	*WL-PC-WTII*
Tilga HOC	0	0	0.2	0.2	1.2	1.2
Jaraikela HOC	0.5	0.5	0.2	0.2	13.7	13.7
Gomlai HOC	0	0	0	0	0	0
Adityapur HOC	0.5	0.5	0	0	0	0
Jamshedpur HOC	0	0	0	0	0	0
Ghatshila HOC	0	0	0	0	0	0

Note: WT I: 50 % of rural and livestock WD is fulfilled by ground water.
WT II: Complete rural and livestock WD are fulfilled by surface water.

Tilga showed no risk in its environmental flow during BAU (Table 6.11). However, it displayed negligible risks in all four of the water-transfer scenarios, covering June in all of them, but also September and November-January under the link-prioritised scenario (Figure 6.6). Jaraikela showed minor, but negligible risks during BAU seen in June and August. It showed reduced risks under the catchment-prioritised scenario which was seen only in June; however, its risk increased considerably under link-prioritised scenarios covering months from June-January, reaching low to moderate risk level. Adityapur showed minor but negligible risks in only BAU scenarios covering August-September. The rest of the catchments exhibited no risk in meeting their environmental WD in any of the scenario considered. Water type showed no influence on the environmental WD of the catchments.

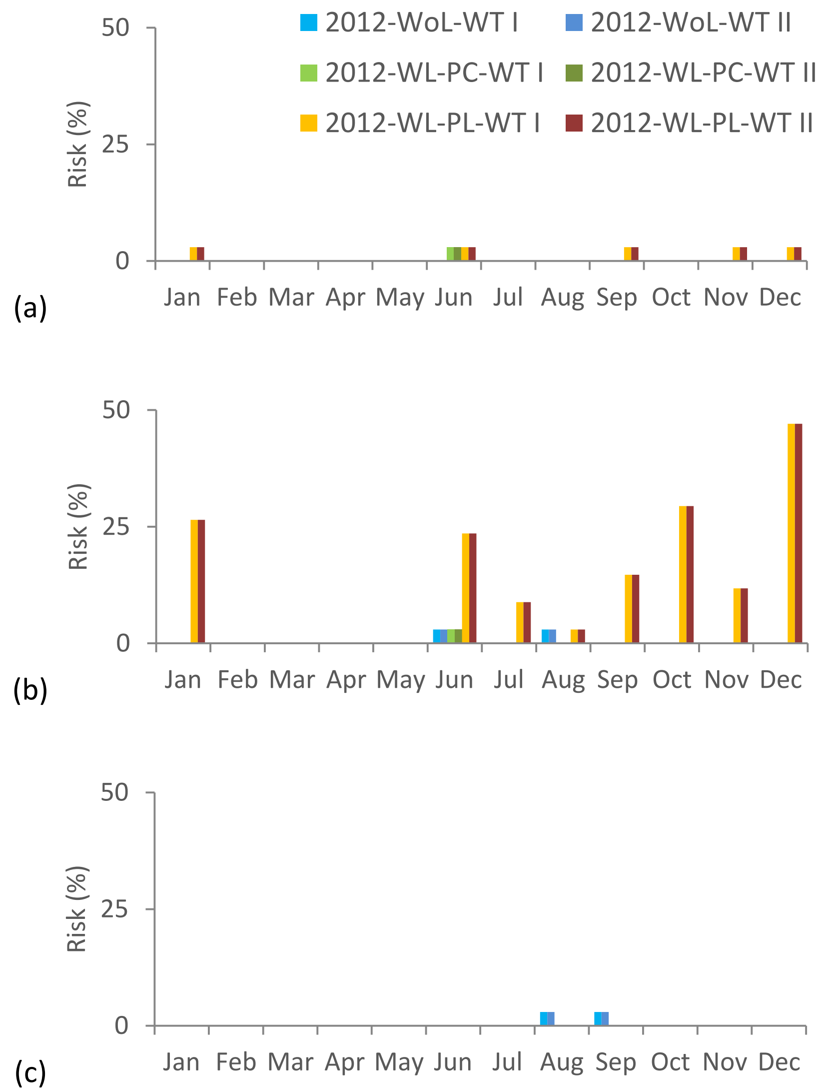


Figure 6.6: Monthly risk (%) in meeting flow requirement at: (a) Tilga (b) Jaraikela and (c) Adityapur during current scenarios.

6.3.2 Risk during probable future scenarios with WD changes

6.3.2.1 In meeting WD of the catchments

The risks in meeting WD of the catchments during probable future scenarios with changes in WD (2050-WD) covered BAU and water-transfer scenarios (Table 6.12 - Table 6.17.).

i) Without ILR links (i.e. during BAU) (2050-WD-WoL)

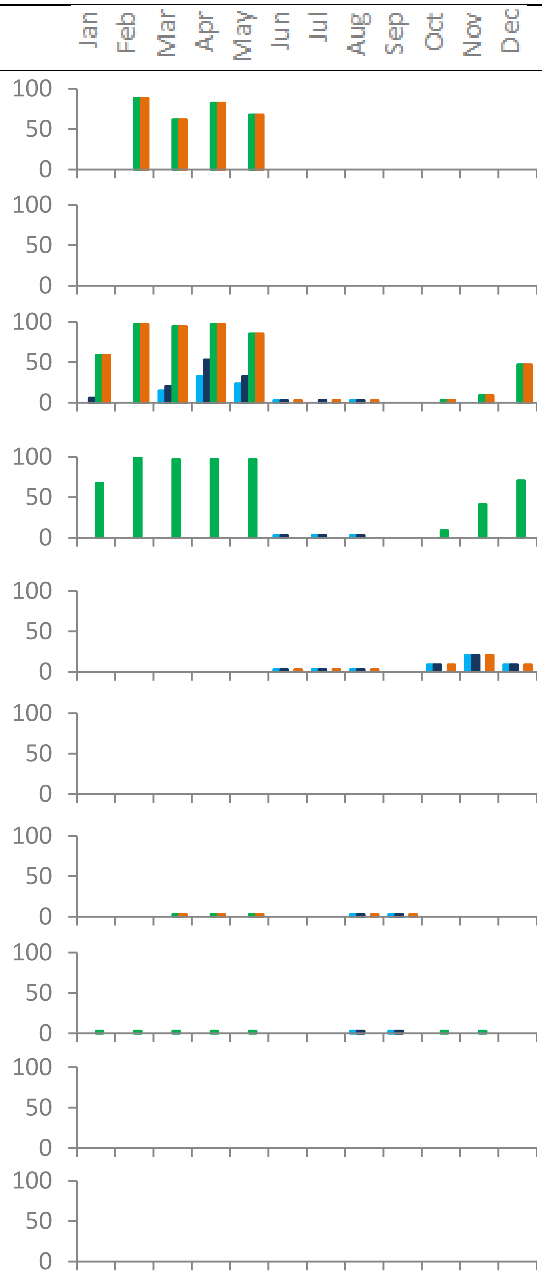
The set of BAU scenarios (2050-WD-WoL) for risks in meeting WD covered two subsets based on the water type (WT I and WT II) (Table 6.12-Table 6.13). During these scenarios, upstream of Tilga and Jaraikela in the donor basin showed considerable increase in the risks to meet their irrigation and industrial WD. Additionally, upstream of Jaraikela showed risks in domestic as well as livestock WD. Their monthly pattern largely remained the same, as seen in current BAU scenarios (Table 6.5-Table 6.6), although the risk level amplified. It also displayed low to moderate risks for domestic and livestock during March-June. The middle sub-catchment of Jaraikela, which showed negligible risks in all of its WD during current BAU scenarios, demonstrated a sudden increase in the risk for irrigation WD during future BAU scenarios with significantly high monthly risk during February-May and low to moderate risk during the rest of the non-monsoonal months (Table 6.12 - Table 6.13). Downstream Jaraikela showed a minor increase in risks for all WD, although they remained negligible. Its monthly risk showed low to moderate risks during October-December and minor risks during the monsoon months. The rest of the donor basin showed no risk in meeting their WD. In the recipient basin, the two sub-catchments of Adityapur showed minor but insignificant risks in all WD as seen in similar current scenarios. They remained negligible at the monthly scale, yet the risks covered more months than the current scenarios. The rest of the recipient catchments showed no risk at all.

The influence of water type remained largely marginal and was thus negligible in all catchments. Only in upstream Jaraikela was low influence displayed, especially in domestic and livestock WD.

Table 6.12: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in probable future scenario with WD change, without ILR links and with water type I (2050-WD-WoL-WT-I)

Catchment	Reach	Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	0	0	24.8	24.8
	Downstream: below S-SK link's start	0	0	-	-
Jaraikela	Upstream: above S-SK link's fall	6.3	10	41	41.7
	Middle: below S-SK link's fall & above SK-Sr link's start	0.7	0.7	47.9	-
	Downstream: below SK-Sr link's start	3.7	3.7	-	3.7
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0.5	0.5	0.7	1.2
	Downstream: below SK-Sr link's fall	0.7	0.7	1.9	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%): 0-25 (%) | 25-50 (%) | 50-75 (%) | 75-100 (%)
Significance: Low | moderate | high | Very high

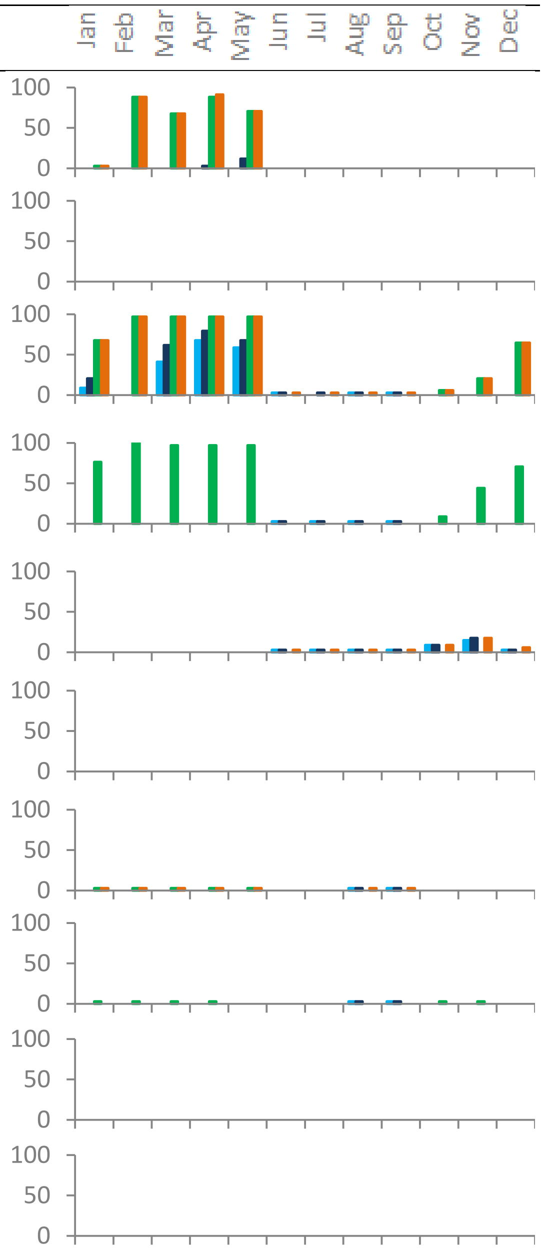
Water use: Domestic, Livestock, Irrigation, Industry

Notes: - No water demand thus no risk.
*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

Table 6.13: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in probable future scenario with WD change, without ILR links and with water type II (2050-WD-WoL-WT-II)

Catchment	Location	Domestic	Livestock	Irrigation	Industry
		Annual risk (%)			
Tilga	Upstream: above S-SK link's start	0	1.2	26.2	26.4
	Downstream: below S-SK link's start	0	0	-	-
Jaraikela	Upstream: above S-SK link's fall	15	19.7	45.4	46.1
	Middle: below S-SK link's fall & above SK-Sr link's start	0.7	0.7	48.8	-
	Downstream: below SK-Sr link's start	2.8	3	-	3.2
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0.7	0.7	1.6	2.3
	Downstream: below SK-Sr link's fall	0.7	0.7	3	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%): 0-25 (%) | 25-50 (%) | 50-75 (%) | 75-100 (%)
Significance: Low | moderate | high | Very high

Water use: Domestic, Livestock, Irrigation, Industry

Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

ii) With ILR links (i.e. during water transfer) (2050-WD-WL)

Water-transfer scenarios (Table 6.14-Table 6.17) were grouped on the basis of priority: their priority to catchment (2050-WD-WL-PC) and their priority to ILR links (2050-WD-WL-PL). Each of them was further grouped by water types, WT I and WT II.

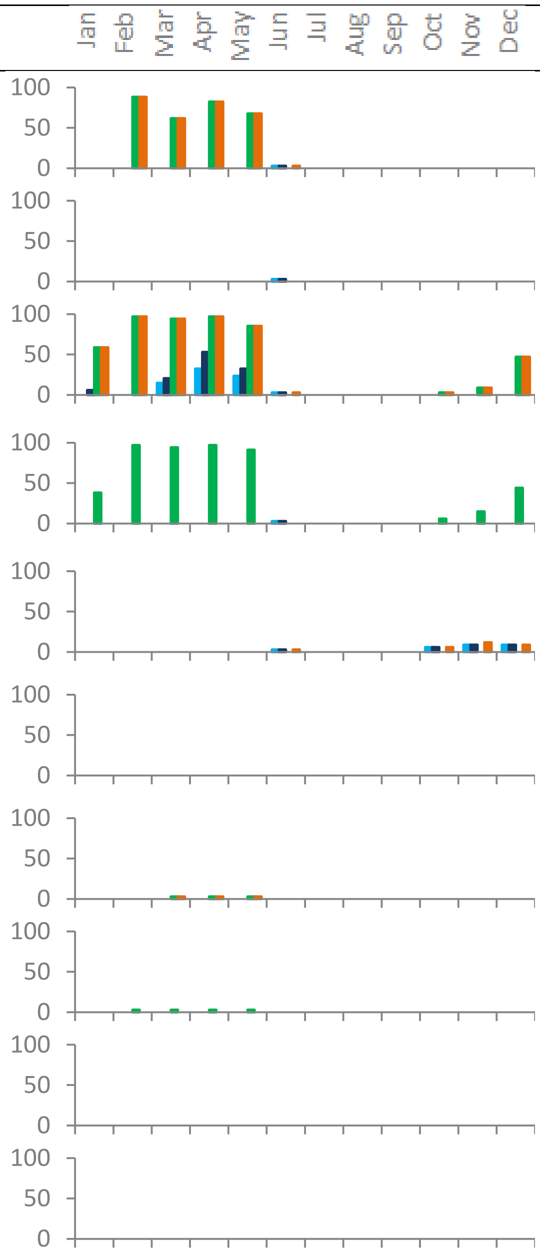
a) Priority given to the WD within the catchments (PC)

The annual and monthly risks in these catchment-prioritised water-transfer scenarios (2050-WD-WL-PC) are given in Table 6.14 and Table 6.15 respectively. When compared to the current period counterpart (2012-WL-PC) scenarios, catchments displayed similar trends within most of their sub-catchments as seen between the BAU and with ILR link scenarios during the current period; with a mild increase in risks seen in Tilga and marginal improvement in the risks seen in Jaraikela and Adityapur. However, it was noticeable that Adityapur, where the minor risks disappeared due to water transfer during current scenarios, kept displaying its negligible risk in future scenarios despite the extra water being transferred to it. The remaining catchments and sub-catchments in the donor and recipient basins showed no risk in any of their WD. Monthly patterns of all the risks in all catchments largely remained the same with higher risks in non-monsoonal months as seen in the current period counterpart however the risk level intensified with time. The influence of water types largely remained similar to that seen in future BAU scenarios.

Table 6.14: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in probable future scenario with WD change, with ILR links (priority catchments) and with water type I (2050-WD-WL-PC-WT-I)

Catchment	Section	Annual risk (%) Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	0.2	0.2	24.8	25
	Downstream: below S-SK link's start	0.2	0.2	-	-
Jaraikela	Upstream: above S-SK link's fall	6	9.5	41	41.2
	Middle: below S-SK link's fall & above SK-Sr link's start	0.2	0.2	40.3	-
	Downstream: below SK-Sr link's start	2.1	2.1	-	2.3
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0	0	0.7	0.7
	Downstream: below SK-Sr link's fall	0	0	0.9	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%) 0-25 (%) 25-50 (%) 50-75 (%) 75-100 (%) Water use Domestic Livestock Irrigation Industry

Significance Low moderate high Very high

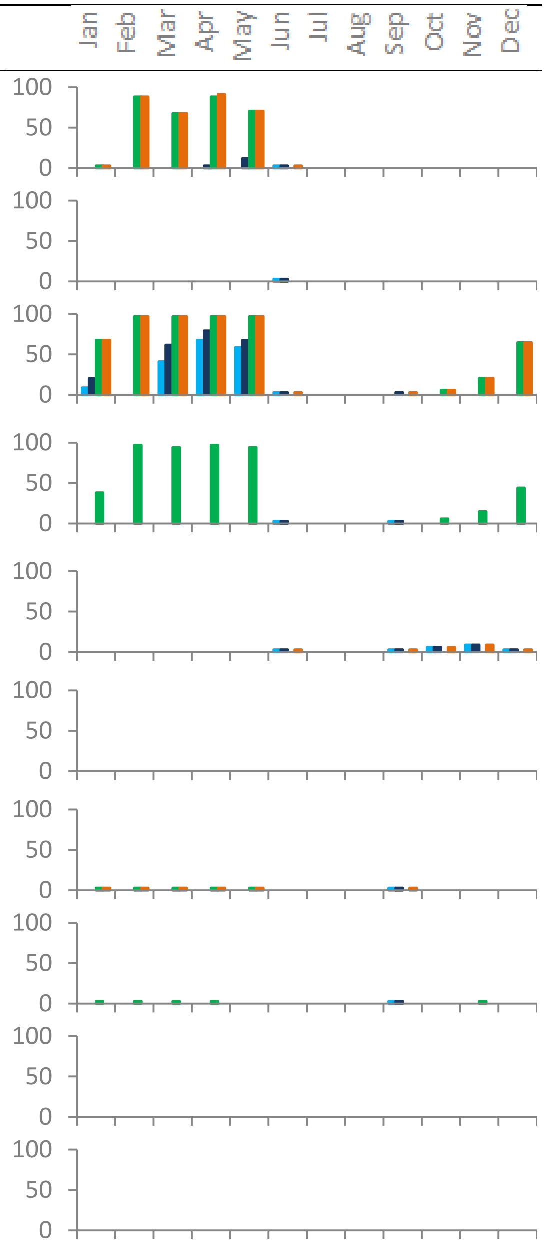
Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

Table 6.15: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in probable future scenario with WD change, with ILR links (priority catchments) and with water type II (2050-WD-WL-PC-WT-II)

Catchment	Location	Annual risk (%): Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	0.2	1.4	26.2	26.6
	Downstream: below S-SK link's start	0.2	0.2	-	-
Jaraikela	Upstream: above S-SK link's fall	14.8	19.4	45.4	45.8
	Middle: below S-SK link's fall & above SK-Sr link's start	0.5	0.5	40.5	-
	Downstream: below SK-Sr link's start	1.9	1.9	-	1.9
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0.2	0.2	1.2	1.4
	Downstream: below SK-Sr link's fall	0.2	0.2	1.2	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%) 0-25 (%) 25-50 (%) 50-75 (%) 75-100 (%)

Significance Low moderate high Very high

Water use: Domestic, Livestock, Irrigation, Industry

Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

b) Priority given to the water transfer by ILR links (PL)

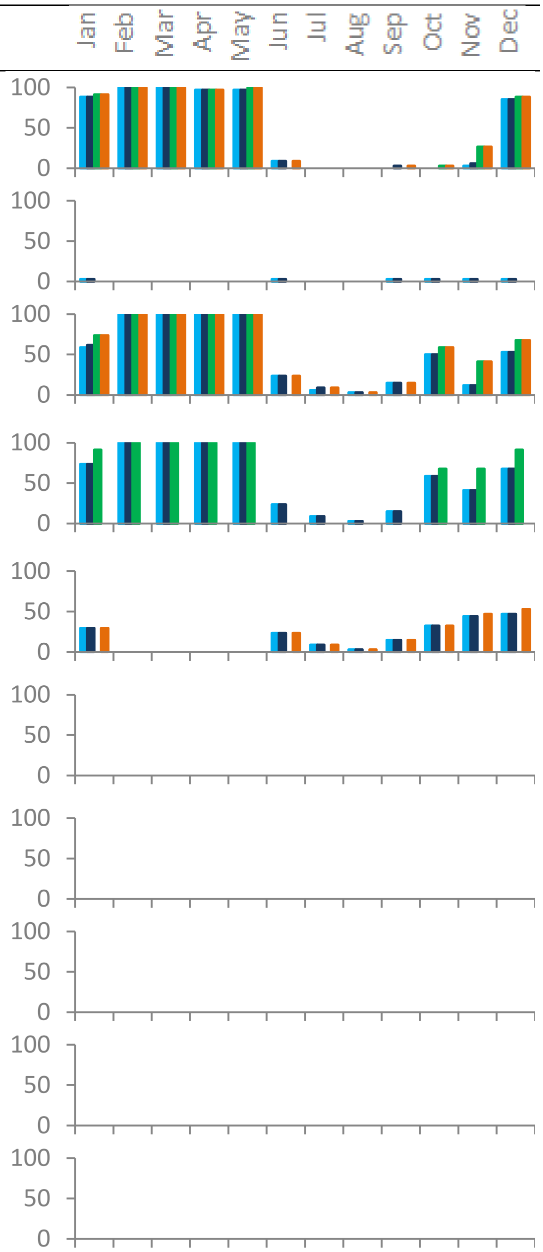
The annual and monthly risks in these link-prioritised water-transfer scenarios (2050-WD-WL-PL) are given in Table 6.16 (for WT I) and Table 6.17 (WT II) respectively. When compared to their current period counterpart (i.e. 2012-WL-PL: Table 6.9-Table 6.10), all sub-catchments of Tilga and Jaraikela indicated a minor increase in the risks for all WD during future scenarios (Table 6.16 and Table 6.17). Adityapur showed no risk in any of its WD. None of the other catchments showed any risk in their WD. Monthly patterns of all the risks in all catchments largely remained the same as seen in similar current scenarios however the risk level increased marginally.

On the other hand, when these with ILR link scenarios were compared to the rest of the probable future scenarios (Table 6.12-Table 6.15), upstream Tilga showed a sharp increase in the risks for all WD increasing them to moderate to significant risk levels (Table 6.16-Table 6.17). Downstream Tilga also showed a minor, but negligible increase in its WD. The monthly risk pattern increased considerably and showed almost 100% risk during December-May. All sub-catchments of Jaraikela exhibited heightened risks in all WD, which were largely significant in the upstream and middle Jaraikela sub-catchments. Similar to Tilga, they displayed a higher monthly risk pattern with 100% risk in all WD during February-May. The upstream and middle Jaraikela sub-catchments displayed substantial risk in all the months ranging from high (in non-monsoon months), to moderate (in monsoon months). Contrary to the other two sub-catchments, downstream Jaraikela exhibited low to moderate risk during June-January and displayed no risk during February-May which is similar to its current scenario. The remaining catchments and sub-catchments in donor and recipient basins showed no risk in meeting their WD. Similar to other scenarios, water types showed a negligible impact on the risks assessed.

Table 6.16: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in probable future scenario with WD change, with ILR links (priority links) and with water type I (2050-WD-WL-PL-WT-I)

Catchment	Location	Annual risk (%) Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	47	47.5	49.5	50.5
	Downstream: below S-SK link's start	1.4	1.4	-	-
Jaraikela	Upstream: above S-SK link's fall	50.5	50.9	52.8	57.2
	Middle: below S-SK link's fall & above SK-Sr link's start	56	56	59	-
	Downstream: below SK-Sr link's start	16.7	16.7	-	17.4
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0
	Downstream: below SK-Sr link's fall	0	0	0	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%)	0-25 (%)	25-50 (%)	50-75 (%)	75-100 (%)
Significance	Low	Moderate	High	Very high

Water use: Domestic, Livestock, Irrigation, Industry

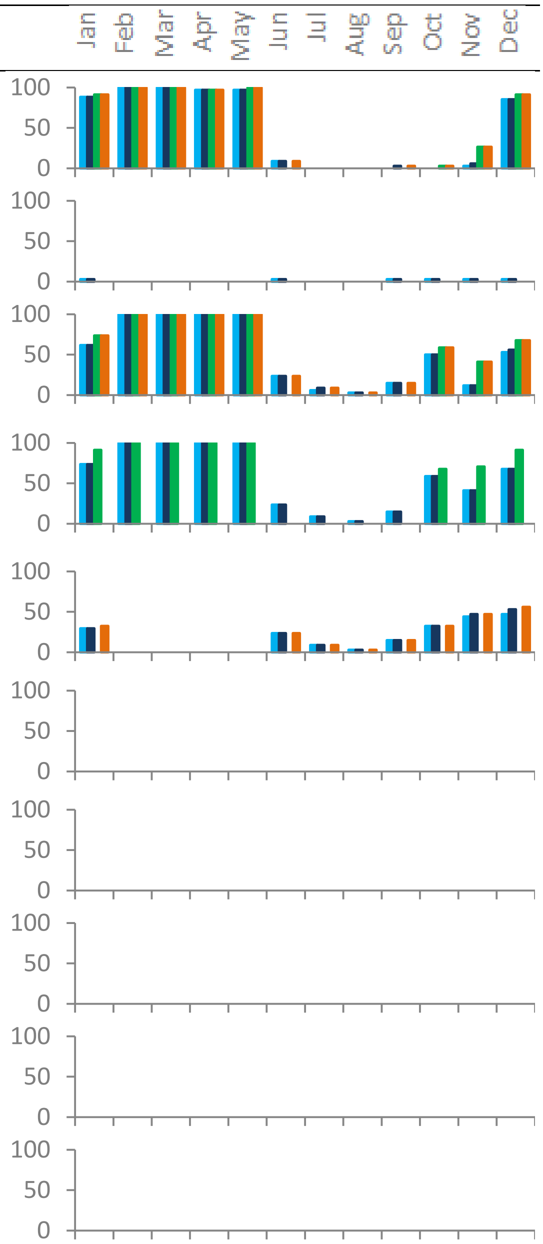
Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

Table 6.17: Risk (%) of catchments in fulfilling their WD for domestic, livestock, irrigation and industry in probable future scenario with WD change, with ILR links (priority links) and with water type II (2050-WD-WL-PL-WT-II)

Catchment	Reach	Annual risk (%) Domestic	Livestock	Irrigation	Industry
Tilga	Upstream: above S-SK link's start	47	47.5	49.8	50.7
	Downstream: below S-SK link's start	1.4	1.4	-	-
Jaraikela	Upstream: above S-SK link's fall	50.7	51.2	52.8	57.2
	Middle: below S-SK link's fall & above SK-Sr link's start	56	56	59.3	-
	Downstream: below SK-Sr link's start	16.7	17.4	-	17.8
Gomlai		0	0	0	0
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0
	Downstream: below SK-Sr link's fall	0	0	0	*-
Jamshedpur		0	0	0	0
Ghatshila		0	0	0	0

Monthly risk (%)



Risk (%) 0-25 (%) 25-50 (%) 50-75 (%) 75-100 (%) Water use Domestic Livestock Irrigation Industry

Significance Low moderate high Very high

Notes: - No water demand thus no risk.

*- Industrial area of Adityapur (downstream of SK-Sr ILR link) is completely within Adityapur Industrial Development Authority (AIDA) and its area within AIDA is not publicly available. Therefore, AIDA is completely included in Ghatshila.

6.3.2.2 In meeting flow requirement of the catchments

The catchments largely fulfilled their flow requirements for environmental WD in BAU as well as water-transfer scenarios during the period of 2050-WD (Table 6.18; Figure 6.7). They depicted similar risks in environmental requirements as seen in the current period (Table 6.11; Figure 6.6) with negligible variation in their intensity.

Table 6.18: Probable future scenario with WD change (2050-WD): Risks in meeting flow requirement (environmental WD) at catchments (measured at their HOCs).

Hydrological Observation Centre (HOC) of each catchment	Risk in meeting required flow during 2050-WD					
	Without ILR link		With ILR link			
	WT I	WT II	Priority catchments		Priority ILR links	
			WT I	WT II	WT I	WT II
Scenarios: 2050-WD-	*WoL-WTI*	*WoL-WTII*	*WL-PC-WTI*	*WL-PC-WTII*	*WL-PL-WTI*	*WL-PC-WTII*
Tilga HOC	0	0	0.2	0.2	1.2	1.2
Jaraikela HOC	0.7	0.7	0.2	0.5	13.7	13.7
Gomlai HOC	0	0	0	0	0	0
Adityapur HOC	0.5	0.7	0	0.2	0	0
Jamshedpur HOC	0	0	0	0	0	0
Ghatshila HOC	0	0	0	0	0	0

Note: WT I: 50 % of rural and livestock WD is fulfilled by ground water.
WT II: Complete rural and livestock WD are fulfilled by surface water.

When compared to current period BAU scenarios (Table 6.11; Figure 6.6), Tilga showed no change at all at either annual or monthly scales (Table 6.18; Figure 6.7). However, Jaraikela showed only a marginal increase in risks for environmental flow which was seen in July, although the risks remained negligible (Table 6.18). A similar negligible risk was maintained under catchment-prioritised water transfer with a minor increase seen in WT II which was evident in September. Under link-prioritised scenarios, Jaraikela maintained the same risks as seen in the current period counterpart scenarios. Adityapur showed relatively similar risks in environmental flow as seen in current scenarios, with some additional risk seen in subset scenarios for WT II under BAU (July) and the catchment-prioritised water-transfer scenario (September). The other catchments showed no risk in any of the scenarios.

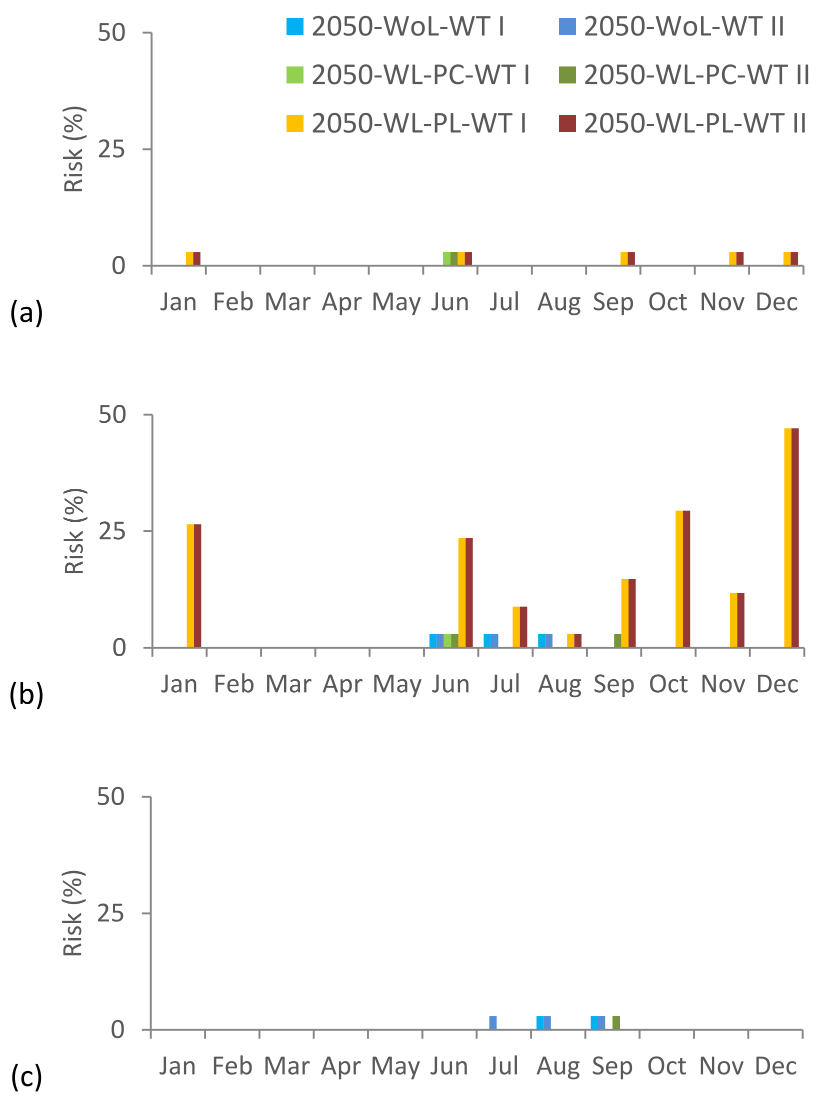


Figure 6.7: Monthly risk (%) in meeting flow reuirement at: (a) Tilga (b) Jaraikela (c) jaraikela during probable future scenarios with WD change.

6.3.3 Influence of climate change on the risks during probable future scenarios

The possible influence of climate change (CC) on the risks in meeting different WD in the future was explored by simulating links and catchments under six probable future scenarios with changes in WD and climate (2050-WD-CC). The simulation was carried out for RCP 2.6 and RCP 8.5 (Table 6.3) using generalised simulated data for maximum precipitation change provided by Chaturvedi et al. (2012).

Noticeably, the modelling inputs related to maximum precipitation change were the same for almost all catchments (+5%) under both RCP except for Gomlai in RCP 2.6 (-5%). Further, similar to both 2012 and 2050-WD scenario-sets, Gomlai, Jamshedpur and Ghatshila showed no risk in any of its WD during 2050-WD-CC. Thus, these catchments are not included in further description. Hence, the modelling outputs for Tilga, Jaraikela and Adityapur from both RCPs during future scenarios are collectively described here. In order to explore the influence of CC on the future risks in meeting different WD, the outputs from the 2050-WD-CC were compared with their counterparts from 2050-WD (Table 6.12-Table 6.17). Due to the insignificant climate change influences on an annual basis, and also due to the absence of monthly climate change data at catchment level, influence of CC at the monthly scale was not explored.

6.3.3.1 Influence of climate change on the risk in meeting WD of the catchments

It was observed that due to climate change, the risks reduced marginally although these reductions were insignificant (Table 6.19-Table 6.21).

Table 6.19: Influence of climate change: possible improvement in risks (%) for different WD in catchments under future without ILR link scenario (2050-WD-WoL).

Catchments / scenarios 2050-WD -WoL	Possible improvement in annual risk (%) for different WD due to risk reduction as a result of climate change							
	Domestic		Livestock		Irrigation		Industry	
	WT I	WT II	WT I	WT II	WT I	WT II	WT I	WT II
Tilga	Upstream: above S-SK link’s start							
	0	0	0	1.2	1.9	0.9	1.85	1.2
	Downstream: below S-SK link’s start							
	0	0	0	0	-	-	-	-
Jaraikela	Upstream: above S-SK link’s fall							
	2.5	2.3	1.9	1.2	1.4	2.1	1.6	2.3
	Middle: below S-SK link’s fall & above SK-Sr link’s start							
	0.2	0.2	0.2	0.2	0.9	1.2	-	-
	Downstream: below SK-Sr link’s start							
	0.9	0.7	0.9	0.9	-	-	0.5	0.9
Adityapur	Upstream: above SK-Sr link’s fall							
	0	0	0	0	0	0.7	0	0.7
	Downstream: below SK-Sr link’s fall							
	0.2	0	0.2	0	0.2	1.2	*-	*-

Table 6.20: Influence of climate change: possible improvement in risks (%) for different WD in catchments under future catchment-prioritised with ILR link scenario (2050-WD-WL-PC).

Scenarios for 2050-WD- WL-PC		Possible improvement in annual risk (%) for different WD due to risk reduction as a result of climate change							
		Domestic		Livestock		Irrigation		Industry	
		WT I	WT II	WT I	WT II	WT I	WT II	WT I	WT II
Tilga	Upstream: above S-SK link's start	0	0	0	1.2	1.9	0.9	1.85	1.2
	Downstream: below S-SK link's start	0	0	0	0	-	-	-	-
Jaraikela	Upstream: above S-SK link's fall	2.5	2.3	1.6	1.2	1.4	2.1	1.4	2.3
	Middle: below S-SK link's fall & above SK-Sr link's start	0	0.2	0	0.2	2.1	1.6	-	-
	Downstream: below SK-Sr link's start	0.5	0.5	0.5	0.5	-	-	0.5	0.5
Adityapur	Upstream: above SK-Sr link's fall	0	0.2	0	0.2	0.7	1.2	0.7	1.4
	Downstream: below SK-Sr link's fall	0	0.2	0	0.2	0.9	1.2	*-	*-

Table 6.21: Influence of climate change: possible improvement in risks (%) for different WD in catchments under future link-prioritised with ILR link scenario (2050-WD-WL-PL).

Scenarios for 2050-WD- WL-PL		Possible improvement in annual risk (%) for different WD due to risk reduction as a result of climate change							
		Domestic		Livestock		Irrigation		Industry	
		WT I	WT II	WT I	WT II	WT I	WT II	WT I	WT II
Tilga	Upstream: above S-SK link's start	1.6	1.6	1.9	1.2	0.9	1.2	1.2	1.4
	Downstream: below S-SK link's start	0.2	0.2	0.2	0.2	-	-	-	-
Jaraikela	Upstream: above S-SK link's fall	1.6	1.9	1.9	1.9	1.4	1.2	1.6	1.4
	Middle: below S-SK link's fall & above SK-Sr link's start	1.2	1.2	1.2	1.2	0.9	1.2	-	-
	Downstream: below SK-Sr link's start	1.2	1.2	1.2	1.6	-	-	1.6	1.9
Adityapur	Upstream: above SK-Sr link's fall	0	0	0	0	0	0	0	0
	Downstream: below SK-Sr link's fall	0	0	0	0	0	0	*-	*-

Although catchments demonstrated very marginal reductions in risks, Jaraikela showed the maximum improvement during BAU (Table 6.19) and catchment-prioritised water-transfer scenarios (Table 6.20), which reduced in link-prioritised water-transfer (Table 6.21). The WD for irrigation and industry were largely benefitted across all six scenarios (Table 6.19-Table 6.21).

6.3.3.2 Influence of climate change on the risk in meeting flow requirements of catchments

The risks in flow requirements for environmental WD by the catchments displayed the positive influence of climate change, although the magnitude of influence was negligible in all catchments and scenarios (Table 6.22). Tilga showed no influence of CC in either future BAU or catchment-prioritised water-transfer scenarios. Jaraikela experienced the largest, but still negligible benefit of CC among the three catchments. Both catchments showed a negligible decrease in the risks in link-prioritised water-transfer scenarios. Adityapur also demonstrated a very minor decrease in BAU and catchment-prioritised water-transfer scenario with WT II.

Table 6.22: Influence of climate change: possible improvement in risks (%) for flow requirement of catchments under future scenario (2050-WD).

Hydrological Observation Centre (HOC) of each catchment	Possible improvement in annual risk (%) for flow requirement due to climate change					
	Without ILR link		With ILR link			
	WT I	WT II	Priority catchments		Priority ILR links	
			WT I	WT II	WT I	WT II
Scenarios: 2050-WD-	*WoL-WTI*	*WoL-WTII*	*WL-PC-WTI*	*WL-PC-WTII*	*WL-PL-WTI*	*WL-PC-WTII*
Tilga HOC	0	0	0	0	0.5	0.5
Jaraikela HOC	0.2	0.2	0	0.2	2.3	2.3
Adityapur HOC	0	0.2	0	0.2	0	0

Note: WT I: 50 % of rural and livestock WD is fulfilled by ground water.
WT II: Complete rural and livestock WD are fulfilled by surface water.

6.4 The ILR links: Risk and vulnerability

The two ILR links, S-SK and SK-Sr were examined for their risks and vulnerability in fulfilling the proposed water transfer (NWDA 2009a, 2009b) and were grouped on the basis of priority: priority to catchment and priority to ILR links. Each of them included scenarios for water types, WT I and WT II. The annual and monthly risks for ILR links were observed under current (2012) and future scenarios (2050) comprising future risks due to change in WD (2050-WD) as well as the influence of climate change on the risks observed during 2050-WD (i.e. 2050-WD-CC).

6.4.1 Risk in meeting the proposed flow by ILR links

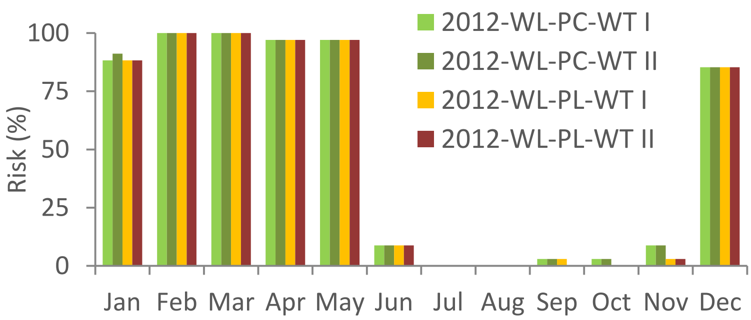
6.4.1.1 Risks during current scenarios

Both ILR links showed considerably higher risk in meeting their proposed water transfer (Table 6.23-Table 6.24) during the four current water-transfer scenarios (subsets of priority to catchments (2012-WL-PC) and priority to links (2012-WL-PL)).

i) Sankh-South Koel (S-SK) ILR link

The S-SK link demonstrated 47-48.1% risk at the annual level (Table 6.23). The link showed a marginally higher risk in catchment-prioritised scenarios. The monthly risk pattern of the link showed a significant risk level during December-May, rising to around 100% during February-May. Minor risk was also seen in the rest of the non-monsoon months largely in catchment-prioritised scenarios. Additionally, it demonstrated low risk in June (early monsoon season). During catchment-prioritised scenario of water type II, S-SK showed a marginal increase in the risk in January, however, it was negligible.

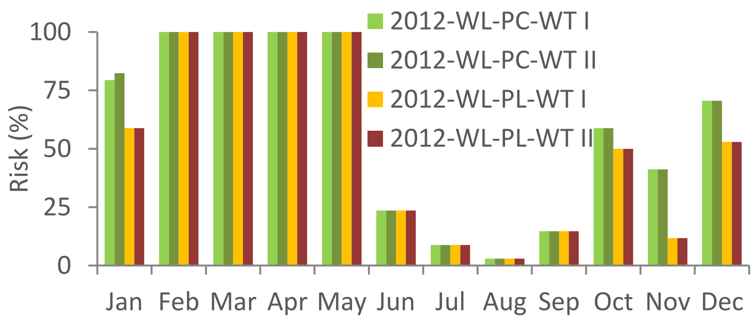
Table 6.23: Sankh-South Koel ILR link: Risk (%) in meeting proposed monthly water in current 'with ILR link' scenario (2012-WL)

S-SK ILR link: Risk (%) in meeting proposed water during 2012-WL		
Annual		Monthly
Priority to Catchment (PC)		
Water type I (WT I)	47.9	
Water type II (WT II)	48.1	
Priority to Links (PL)		
Water type I (WT I)	47.2	
Water type II (WT II)	47	

ii) South Koel-Subarnarekha (SK-Sr) ILR link

The SK-Sr link demonstrated 50.7-56.9% risk at the annual level (Table 6.24). In all four water-transfer scenarios, the link displayed marginally higher risk than the S-SK link. Further, it showed relatively higher risk in the catchment-prioritised scenarios. Its monthly risk pattern showed substantial risk in both the monsoon and non-monsoon seasons, reaching to around 100% during February-May. A highly significant risk was present in October and December-May and there was a low to moderate risk in the rest of the months, especially during catchment-prioritised scenarios. Similar to the S-SK link, the SK-Sr link also showed marginal influence of water type II on the risk in January.

Table 6.24: South Koel-Subarnarekha ILR link: Risk (%) in meeting proposed monthly water in current 'with ILR link' scenario (2012-WL)

<table>
<tr><th colspan="3">SK-Sr ILR link: Risk (%) in meeting proposed water during 2012-WL</th></tr>
<tr><th colspan="2">Annual</th><th>Monthly</th></tr>
<tr><td colspan="2">Priority to Catchment (PC)</td><td rowspan="7">
</td></tr>
<tr><td>Water type I (WT I)</td><td>56.7</td></tr>
<tr><td>Water type II (WT II)</td><td>56.9</td></tr>
<tr><td colspan="2">Priority to Links (PL)</td></tr>
<tr><td>Water type I (WT I)</td><td>50.7</td></tr>
<tr><td>Water type II (WT II)</td><td>50.7</td></tr>
</table>

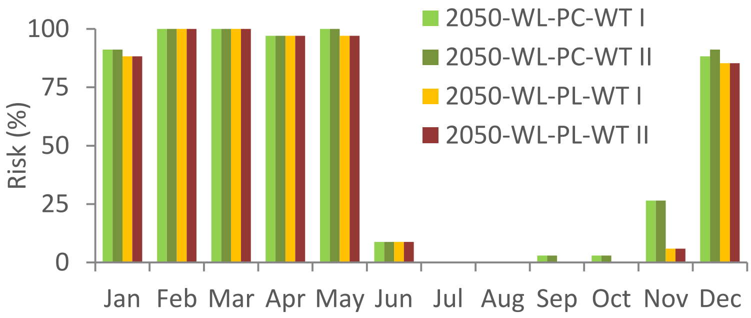
6.4.1.2 Risks during future scenarios

When compared to the current scenario counterpart, both ILR links showed higher risk in meeting their proposed water transfer (Table 6.23-Table 6.24; Table 6.25-Table 6.26) during the four future water-transfer scenarios grouped under two sets, priority to catchments (2050-WD-WL-PC) and priority to links (2050-WD-WL-PL).

i) Sankh-South Koel (S-SK) ILR link

When compared to current scenarios, the S-SK link demonstrated a marginal increase in risk at the annual level (Table 6.23; Table 6.25), largely evident in catchment-prioritised water-transfer scenarios covering May and November-January. In the other months, the link followed the same monthly pattern as seen in current scenarios. During catchment-prioritised scenario for water type II, a negligible increase in risk was seen in December instead of January.

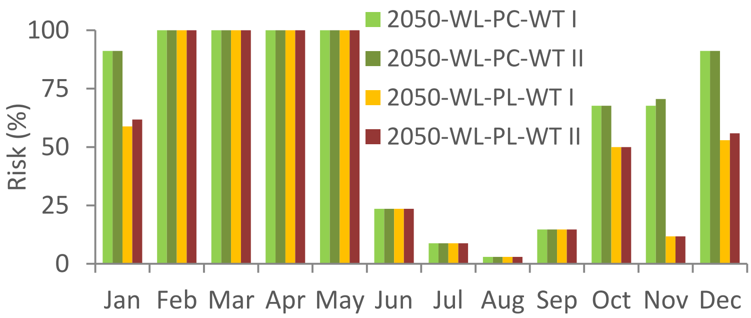
Table 6.25: Sankh-South Koel ILR link: Risk (%) in meeting proposed monthly water in future with ILR link scenario (2050-WD)

S-SK ILR link: Risk (%) in meeting proposed water during 2050-WD-WL		
Annual		Monthly
Priority to Catchment (PC)		
Water type I (WT I)	50	
Water type II (WT II)	50.2	
Priority to Links (PL)		
Water type I (WT I)	47.2	
Water type II (WT II)	47.2	

ii) South Koel-Subarnarekha (SK-Sr) ILR link

The SK-Sr link displayed a relatively higher risk than that of S-SK link in comparison to the difference seen in the current period (Table 6.24; Table 6.26).

Table 6.26: South Koel-Subarnarekha ILR link: Risk (%) in meeting proposed monthly water in the future with ILR link scenario (2050-WD-WL)

SK-Sr ILR link: Risk (%) in meeting proposed water during 2050-WD-WL		
Annual		Monthly
Priority to Catchment (PC)		
Water type I (WT I)	62.3	
Water type II (WT II)	62.5	
Priority to Links (PL)		
Water type I (WT I)	50.7	
Water type II (WT II)	51.2	

Similar to the current scenarios, the SK-Sr link displayed a considerable increase in the risk at the annual scale (Table 6.24; Table 6.26). It was due to a sharp increase in the risk under catchment-prioritised scenarios that is evident in October-January. The monthly pattern largely remained similar and showed a significant risk in both the monsoon and non-monsoon seasons. Similar to the S-SK link, marginal but negligible increase in risks were noted during catchment-prioritised water type II scenarios in January and November.

6.4.1.3 Influence of climate change

Similar to sections 6.3.3.1-2, both ILR links demonstrated minor reductions in the risk in meeting proposed water transfers across all four water-transfer scenarios albeit the magnitude remained insignificant (Table 6.27). They showed some improvement in the link-prioritised water-transfer scenarios.

Table 6.27: Influence of climate change: possible improvement in risks (%) for proposed monthly water transfer by the two ILR links (Source: NWDA 2009a; NWDA 2009b) under future water-transfer scenario (2050-WD).

ILR links	Possible improvement in annual risk (%) for proposed monthly water due to climate change			
	Priority catchments		Priority ILR links	
	WT I	WT II	WT I	WT II
Scenarios 2050-WD-	*WL-PC-WTI*	*WL-PC-WTII*	*WL-PL-WTI*	*WL-PC-WTII*
Sankh-South Koel	1.2	1.4	1.6	1.6
South Koel-Subarnarekha	0.9	1.2	1.6	1.9

Note: WT I: 50 % of rural and livestock WD is fulfilled by ground water.
WT II: Complete rural and livestock WD are fulfilled by surface water.

6.4.2 Vulnerability in ILR links

After risk assessment, the two ILR links were examined for their likelihood of failure in transferring the proposed water at the annual and monthly scale during all four water-transfer scenarios covering the two subsets priority to catchments and priority to links (Table 6.28-Table 6.31). They are described below.

6.4.2.1 Vulnerability during current scenarios

Both ILR links showed considerable vulnerability during current water-transfer scenarios (Table 6.28-Table 6.29) covering subsets for priority to catchments (2012-WL-PC) and priority to links (2012-WL-PL).

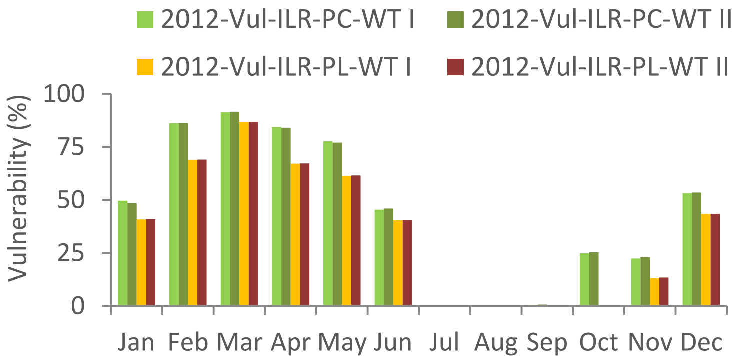
The S-SK link demonstrated 33.3-45.1% vulnerability at the annual level with a relatively high vulnerability level in catchment-prioritised water-transfer scenarios (Table 6.28). When examined at the monthly scale, the vulnerability of the link was highly significant during February-May and remained significant in the other non-monsoon months except November. Low vulnerability was seen during October-November. A negligible influence of water type was seen in November-January.

Table 6.28: Sankh-South Koel ILR link: Vulnerability (%) of the link in meeting proposed monthly water under current with ILR link scenarios (2012-WL)

S-SK ILR link: Vulnerability (%) of the link under 2012-WL

Annual	
Priority to Catchment (PC)	
Water type I (WT I)	40.6
Water type II (WT II)	40.7
Priority to Links (PL)	
Water type I (WT I)	33.3
Water type II (WT II)	33.3

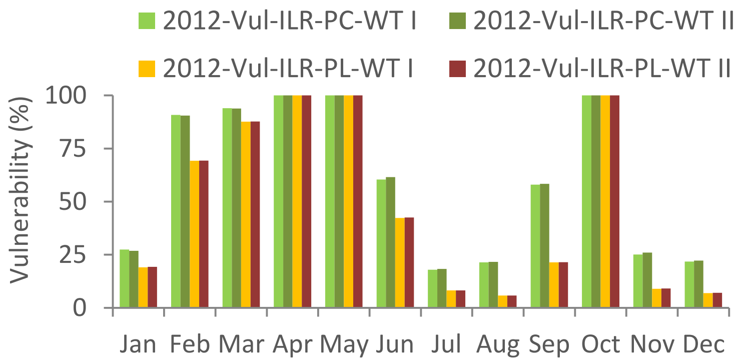
Monthly



The SK-Sr link demonstrated 42.7-56.8% vulnerability at the annual scale (Table 6.29). It displayed higher annual vulnerability than S-SK in all four scenarios. Similar to the S-SK link, the link demonstrated higher vulnerability in catchment-prioritised water-transfer scenarios. At the monthly scale, the link displayed 100% vulnerability during April-May and October, highly significant vulnerability in February-March and low to moderate in rest of the months. Influence of water type was negligible.

Table 6.29: South Koel-Subarnarekha ILR link: Vulnerability (%) of the link in meeting proposed monthly water under current with ILR link scenarios (2012-WL)

SK-Sr ILR link: Vulnerability (%) of the link 2012-WL		
Annual		Monthly
Priority to Catchment (PC)		
Water type I (WT I)	56.8	
Water type II (WT II)	57	
Priority to Links (PL)		
Water type I (WT I)	42.7	
Water type II (WT II)	42.7	



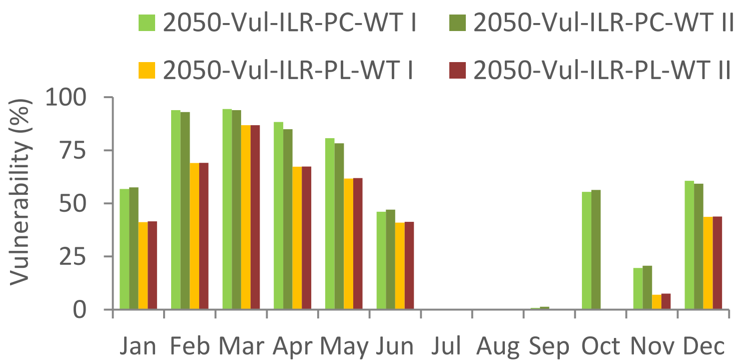
6.4.2.2 Vulnerability during future scenarios

When compared to the current scenario counterpart, both ILR links demonstrated an increase in their vulnerability in meeting their proposed water transfers during the four future water-transfer scenarios comprising scenario sets for priority to catchments (2050-WD-WL-PC) and priority to links (2050-WD-WL-PL).

When compared to its current period counterpart, the annual vulnerability of the S-SK link increased marginally (Table 6.28; Table 6.30).

Table 6.30: Sankh-South Koel ILR link: Vulnerability (%) of the link in meeting proposed monthly water in future with ILR link scenarios (2050-WD-WL)

S-SK ILR link: Vulnerability (%) of link under 2050-WD-WL		
Annual		Monthly
Priority to Catchment (PC)		
Water type I (WT I)	45.1	
Water type II (WT II)	44.8	
Priority to Links (PL)		
Water type I (WT I)	33.1	
Water type II (WT II)	33.2	

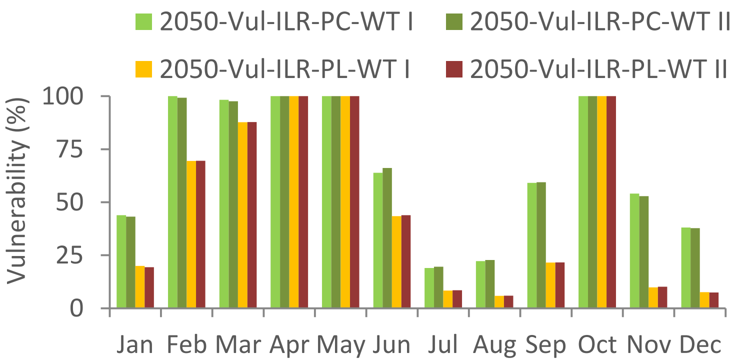


However when examined at the monthly level, the link showed higher vulnerability in catchment-prioritised water-transfer scenarios (Table 6.28; Table 6.30). The link followed a similar monthly vulnerability pattern as seen in the current period however it registered a noticeable increase in October. Negligible influence of water type was seen in non-monsoon months.

Similar to the current period, the SK-Sr link displayed a higher increase in vulnerability which was relatively higher in the catchment-prioritised scenarios (Table 6.29; Table 6.31). The monthly pattern remained similar to that seen in the current period however a relative increase was seen in all months which did not show 100% vulnerability during the current period. Vulnerability seen in February-March increased to 100%. Early non-monsoon months showed significant increase in vulnerability. Influence of water type was negligible.

Table 6.31: South Koel-Subarnarekha ILR link: Vulnerability (%) of the link in meeting proposed monthly water in future with ILR link scenarios (2050-WD-WL)

SK-SR ILR link: Vulnerability (%) of link under 2050-WD-WL		
Annual		Monthly
Priority to Catchment (PC)		
Water type I (WT I)	62.4	
Water type II (WT II)	62.3	
Priority to Links (PL)		
Water type I (WT I)	42.9	
Water type II (WT II)	43	



6.5 Discussion

The research undertaken simulated the proposed S-SK-Sr ILR project in order to examine the annual and monthly performances of the links and catchments under a range of current and future scenarios covering several management policies (without and with ILR links; priorities to catchments or ILR links; and two types of water source to meet rural and livestock WD). The performance of the catchment was assessed by the risks in meeting their WD and environmental flow requirements. The performance of individual links was examined by using the risk in meeting their proposed water transfer. The links were also examined for their annual and monthly vulnerabilities. The possible influence of climate change in future WD was also assessed (on annual basis only due to the absence of monthly climate change data at catchment level), along with the assumption made by NWDA (2009a; 2009b) related to the water type used 'to fulfil 50% of rural WD' .

6.5.1 The performance of catchments

The results suggest that one donor catchment, Gomlai, and two recipient catchments, Jamshedpur and Ghatshila, showed no risk in meeting their WD in any of the scenarios considered. The other two donor catchments, Tilga (two sub-catchments) and Jaraikela (three sub-catchments), and one recipient catchment, Adityapur (two sub-catchments) demonstrated variable performances under different scenarios; the results suggest that demand can exceed supply.

6.5.1.1 Without ILR links (i.e. during BAU)

The findings from the BAU scenarios suggest the performance of catchments in the cases when no ILR links are operating. The outcome from BAU scenarios suggest that both Tilga and Jaraikela experienced risks in meeting some of their existing WD in current, as well as in future scenarios, while Adityapur showed negligible risks.

1. In Tilga, the upstream sub-catchment faced a low risk in meeting irrigational and industrial WD during current scenarios, which amplified to a moderate level with time, especially during February-May in the non-monsoon season. The catchment of Tilga showed no risk in fulfilling its environmental flow requirement in both current and future BAU scenarios.
2. In Jaraikela, the upstream sub-catchment experienced moderate risk in meeting irrigation and industrial WD, but only slight risk in meeting domestic and livestock WD during current scenarios, but risk was exacerbated significantly in future scenarios. Monthly risk was amplified in the non-monsoon months, especially during February-May. The middle

Jaraikela catchment demonstrated a substantial increase in the risk for irrigation WD during future scenarios, with significant monthly risk in the non-monsoon season. The downstream Jaraikela sub-catchment also demonstrated marginal increasing trends in the risks with time; although risk calculated at the annual scale remained negligible. The sub-catchment showed a low to moderate monthly risk pattern in all WD during October-December. Noticeably, all sub-catchments in Jaraikela demonstrated negligible monthly risks in relatively all WD during monsoon months in both current as well as future BAU scenarios. The catchment of Jaraikela showed a negligible risk in fulfilling its environmental flow requirement in June and August during both current and future BAU scenarios.

3. In contrast, Adityapur displayed insignificant risks for all WD including environmental flow requirement at both the annual and monthly level during current as well as future scenarios.

A possible explanation for these risks could be the intra-annual and inter-annual cycles witnessed in the catchments which have been observed by the hydrological analysis of the catchments (section 4.4), also noted by Wadood & Kumari (2009). For the negligible risks noticed during monsoon months in the sub-catchments of Jaraikela, another possible explanation could be the increased environmental flow requirements of the South Koel river during the monsoon months (Smakhtin & Anputhas 2006). Moreover, it is established that the WD within the catchments increased with time and so did the risks of fulfilling them; such as the increase in irrigational WD of the middle Jaraikela sub-catchment which could be attributed to the independently planned irrigation projects in the catchment (NWDA 2009a; 2009b). Thus the performances of both main donor catchments, Tilga and Jaraikela, during the BAU scenarios indicate that the two catchments need management interventions to overcome their evolving risks. On the other hand, the performances of the recipient catchments do not indicate any urgent need to import water from outside the basin.

6.5.1.2 With ILR links (i.e. water-transfer scenarios)

The results from the water-transfer scenarios suggest the performance of catchments when the ILR links start functioning. The outcomes from catchment-prioritised water-transfer scenarios suggest that performance of the catchments varied only slightly from their respective BAU scenarios during current and future periods; they largely followed similar annual and monthly patterns. In addition to the changes seen with time in BAU scenarios, some other changes were also noticed:

1. Sub-catchments of Tilga displayed a marginal increase in the risks of all WD, and the catchment registered insignificant risk in the environmental flow.
2. Sub-catchments of Jaraikela showed marginal reductions in their risks including the noticed disappearance of negligible risks seen in monsoon months.
3. The catchment of Jaraikela showed a mild but negligible increase in the risk for environmental flow especially in July.
4. The marginal risks observed in Adityapur, including the risk in environmental flow, were reduced. However, the impact varied with time resulting in no risk during the current period while exhibiting reduced risk in the future, although the risks remained negligible.

These changes could be explained by the water transfers from/to the sub-catchments of Tilga, Jaraikela and Adityapur. However, as the priority is given to the WD within the catchments, these changes have only minor impacts.

On the other hand, the outcomes from the link-prioritised water-transfer scenarios suggest that the performance of Tilga and Jaraikela changed dramatically:

1. Both catchments showed a sharp increase in the risks for their all WDs in both current as well future scenarios. Unlike the catchment-prioritised water-transfer scenarios, hardly any risk reductions were seen in the sub-catchments of Jaraikela during link-prioritised water transfer.

2. Both catchments registered a significantly increased monthly risk pattern in current as well as future scenarios; especially during the non-monsoonal season, reaching the maximum level of risks in all WD during February-May. Only the downstream sub-catchment of Jaraikela was an exception and showed no risk in its WD during February-May. This could be attributed to the lower environmental flow requirement of the South Koel river during these months (Smakhtin & Anputhas 2006), corroborated by the risks assessed for environmental flow in Jaraikela which suggested no environmental risk during February-May, despite showing considerable risks during the rest of the months.
3. Interestingly, the slight risk which had been noted in the sub-catchments of Jaraikela during monsoon months in both current and future BAU scenarios that disappeared during the catchment-prioritised water-transfer scenarios reappeared in the link-prioritised water-transfer scenarios; there was a considerable increase in comparison to the BAU scenarios. These changes could be attributed to the joint impact of giving higher priority to water transfer through links, as well as the high environmental requirement of the South Koel River during the monsoon months (Smakhtin & Anputhas 2006).
4. In contrast to these two donor catchments, the Adityapur recipient catchment showed a positive change in both current as well as future link-prioritised scenarios as the minor risks seen in the catchment vanished as a result of receiving water through the SK-Sr ILR link.

Thus it is apparent that the performances of both main donor catchments, Tilga and Jaraikela, could deteriorate further from their BAU conditions due to the water transfers from these catchments, especially when water transfer is prioritised over the WD within the catchments. On the other hand, although the water transfer to recipient catchments reduces the marginal risks observed in Adityapur, given the negligible magnitude of risks, the recipient catchments do not show any urgent need of water to be imported to them.

6.5.2 The performance of ILR links

The results demonstrate significant risks for both ILR links in meeting their proposed water transfers on both an annual and monthly basis and the risks will increase with time. Furthermore, both ILR links demonstrated a moderately to highly significant likelihood of failure in transferring the planned water, likely failure also worsened with time. Additionally, both of the links showed seasonal variations in their risk and vulnerabilities, revealing critical situations during non-monsoon months (February-May) when the links experienced maximum risk with the highest vulnerability. Moreover, it is important to note that risks are seen even in the monsoon months. The S-SK link demonstrated low risk in early monsoon (June) with considerable vulnerability, while SK-Sr link revealed low to moderate risk and vulnerability in all monsoon months.

In both current and future time periods, the risk and vulnerability observed in the S-SK link were moderate, but significant in the SK-Sr link. The risks of both links can be correlated to the risks seen in their donor catchments. Jaraikela, the donor catchment of SK-Sr link and, Tilga, the donor catchment of S-SK link, exhibited significant risks in meeting WD leading to less water being available for transfer. However, Tilga showed less risk than Jaraikela, and thereby it could provide slightly more water to transfer leading to lesser risk for the links.

When priority was given to the WD within the catchments both of the links faced a higher likelihood of failure as water was first being used within the catchments and only surplus water was available for transfer from the donor catchments via the two ILR links. This probability of failure increased with time, likely to be caused by the increasing risks in meeting WD within the catchments, which in turn leads to less water available for transfer in the future. Even when the ILR links were prioritised, the situation remained more or less the same as both of the ILR links displayed significant risk and vulnerability, albeit the risks were slightly lower than those experienced when catchment WD was prioritised. This situation largely remained the same during current and future time periods.

6.5.3 Influence of climate change and water types

The possibility of climate change influencing the risks in meeting WD by the catchments and two ILR links during probable future scenarios was explored. Results highlighted positive influences on risks observed, although they were negligible. The study used generalised climate data for basic assessment, detailed study in this direction could be highly beneficial for the two ILR projects and for IBWT projects in general (Cosens 2010; Maknoon et al. 2012), especially given the situation when inter-annual cycles of rainfall and flow exhibit the influence of El Niño (section 4.4). The influence of the source of water type used to fulfil 50% of rural and livestock WD, related to the assumption made by NWDA (2009a; 2009b), was observed on the risks seen for the catchments and ILR link; however this influence was negligible. It suggests that although groundwater is not a significant element in the study area, it is important to explore all available resources in the basin including the groundwater (Bharati et al. 2008).

6.6 Summary

The study simulated the two ILR links under study with their catchments in order to evaluate their performances under BAU and water-transfer scenarios during current and future time-periods. Modelling outputs were used to assess the risks in meeting WD of the catchments and proposed water transfers of the two ILR links. Also, the two ILR links were assessed for their likelihood of failure in transferring the proposed water. The present research discovered that:

1. The two main donor catchments, Tilga and Jaraikela, experienced significant risks in meeting their WD during BAU conditions. It indicates that the two catchments need management interventions to overcome their growing risks in meeting their own WD.
2. The identified risks deteriorated further when water transfers commenced. It depicts that the plans to abstract water from these catchments are likely to further deteriorate the already prevailing risk-conditions in these two catchments.

3. Among the recipient catchments, only Adityapur showed some negligible risks in BAU conditions which reduced when water transfer links started functioning. However, given the magnitude of risks, Adityapur does not indicate any urgent need to import water from outside the catchment.
4. Significant risks and vulnerabilities of the S-SK and SK-Sr links at both annual and monthly levels raise critical concerns regarding their success. Both of the links showed substantial risks and vulnerabilities; and only marginal benefits were observed. It indicates that both of the links, if constructed, will fail to justify their huge costs.

On the basis of these results, it can be stated that the S-SK and SK-Sr links fail to meet the fundamental IBWT criteria as their donor catchments themselves are struggling to meet their own WD. Also, as the recipient catchments present no urgent need for water to be transferred to them from outside the basin, it questions the very purpose of the two ILR projects. Moreover, if constructed, the two ILR links will face significant risks and vulnerabilities which bring into doubt the sustainability of the two projects. Therefore, the research advises the ILR planners reconsider their decision regarding these two links and revisit the existing ILR plans before making any final decision.

Chapter 7 Are Sankh-South Koel and South Koel-Subarnarekha ILR projects justified?

7.1 Introduction

This thesis examined the decision-making process of the two Inter-linking of Rivers (ILR) projects proposed by the Government of India (GOI), namely the Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR links. To do this, the thesis carried out three major tasks: explored the current landscape, hydrology and socio-economic aspects of the catchments involved in the two ILR projects (Chapter 4), developed an integrated methodology for the assessment of water availability (WA) and water demand (WD) on the basis of established inter-basin water transfer (IBWT) criteria-sets (Chapter 5) and used this methodology to simulate the two ILR links and their catchments under current and future scenarios (Chapter 6). The three tasks enabled the performances of ILR links and the donor and recipient catchments to be assessed (Chapter 6).

The outcomes from the research are used to critique the existing plans of the two ILR links (NWDA 2009a, 2009b) proposed by the National Water Development Agency (NWDA) in section 7.2. Additionally, the chapter outlines the specific contribution of this thesis (section 7.3 - 7.4) and provides recommendations for evaluating IBWT proposals (section 7.5).

7.2 Critiquing the two existing ILR plans

The National Water Development Agency (NWDA) carried out feasibility studies[1] for S-SK (NWDA 2009a) and SK-Sr ILR links in 2009 (NWDA 2009b). The detailed progress reports (DPRs) of these links have not yet been started (NWDA 2016a; 2017). Details of these two ILR plans are given in Chapter 3 (section 3.4.1) and they are critiqued below using the understanding developed through the research

[1] NWDA (2009a, 2009b) called the studies as pre-feasibility reports. However, these reports have similar details as seen in case of feasibility reports of other ILR links. After these studies, NWDA is planning to work on a detailed progress report (NWDA 2016).

presented. The critique includes: water balance assessment, functioning of the ILR links, data and approach used, and purpose of the water transfer.

7.2.1 Water balance in the study catchments

The existing ILR plans prepared by NWDA (2009a, 2009b) calculated water balance of the catchment areas contributing to each of the two ILR links (i.e. their upstream donor catchments) in order to transfer surplus water from these catchment areas to the Subarnarekha River basin (Figure 7.1).

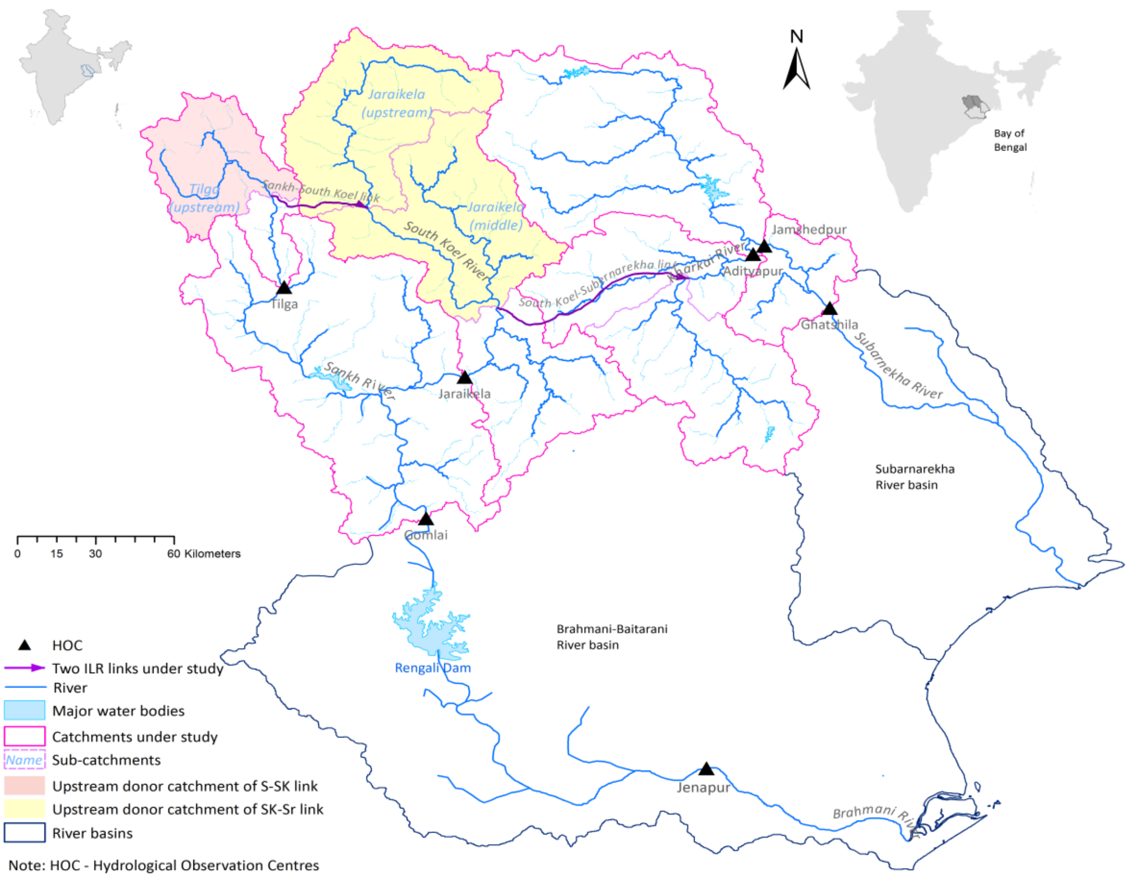


Figure 7.1: The catchment areas contributing to the Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR links as per the existing ILR plans, together with the location of these catchment areas within the catchments under present study and within the major donor and recipient river basins.

These donor catchments are part of the Brahmani-Baitarani River basin[2]. The catchment area contributing to the S-SK ILR link covered the upstream catchment of River Sankh (known as upstream Tilga in the present research). The catchment area contributing to the SK-Sr ILR link covered the upstream catchment of the River South Koel (known as upstream and middle Jaraikela in the present research). For these two contributing catchment areas (i.e. ILR donor catchments), annual water availability was examined (WA) at 75% dependability by NWDA (2009a, 2009b), based on their projected annual water demand (WD) in 2050 and the resultant annual surplus water in the two ILR donor catchments (sections 3.4.1 and 5.2).

7.2.1.1 Annual water availability at 75% dependability

NWDA (2009a, 2009b) calculated annual WA at 75% dependability in the two catchment areas contributing to each of the two ILR links, using annual water-yield data for 34 years based on the annual flow at Jenapur hydrological observation centre (HOC) located 418 km from the S-SK link outflow point and 360 km from the SK-Sr link outflow point (Figure 7.1). The details of their calculation are given in section 3.4.1. The present research assessed WA at 75% dependability in these two catchment areas contributing to each of the two ILR links, using 34-year observed daily flow data at the nearby HOCs: Tilga, 40 km downstream of the outflow of the S-SK link and Jaraikela, 38 km downstream of the outflow of the SK-Sr link (Figure 7.1). The two annual WA outcomes are compared in Figure 7.2. Although, the two annual WA outcomes were similar for the donor catchment of the S-SK link, they differed dramatically for the donor catchment of the SK-Sr link. The marked difference could be attributed to: first, the hydrological behaviour observed in the catchment of Jaraikela (section 4.4) demonstrating low rainfall and low water yield in the catchment which varies from the other parts of the Brahmani-Baitarani basin under study (Figure 7.1) as explored in section 4.4, and second, the influence of spatial and temporal resolution of the data used in these two estimations as discussed in sections 5.2.1.1 and 5.6. On the basis of these two differences and

[2] Brahmani-Baitarani River basin has two sub-basins: Brahmani and Baitarani. The donor catchments of the present study are part of Brahmani sub-basin.

their discussions in respective chapters, it can be stated that the NWDA (2009a, 2009b) over-estimated the WA in the donor catchment of SK-Sr link.

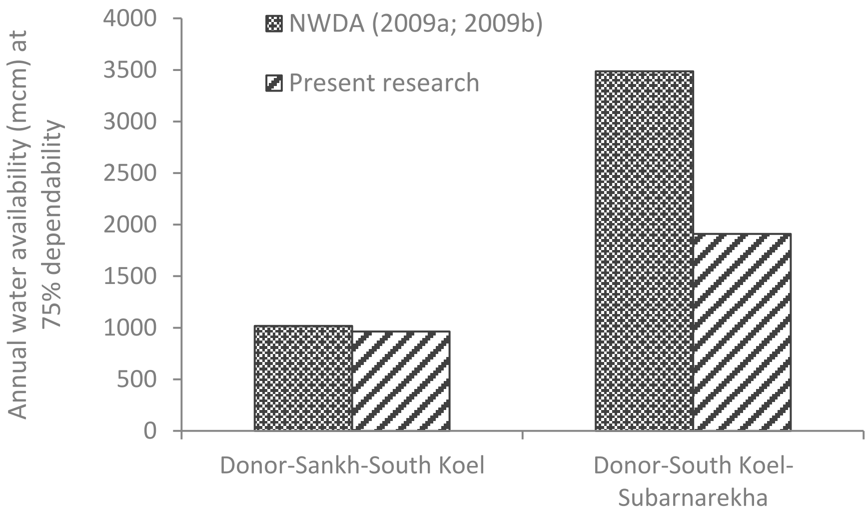


Figure 7.2: Comparison of annual water availability with 75% dependability in the catchment area contributing to the two ILR links.

7.2.1.2 Projected annual water demand in 2050

NWDA (2009a, 2009b) projected WD in 2050 which combined demands for domestic, irrigation, industry water and inflow to the Rengali Dam further downstream. The present research also considered WD for domestic, irrigation and industry purposes in order to calculate the total WD of the catchments in 2050, but also included livestock WD as suggested by Singh (2006). Further, instead of the contribution to the downstream Rengali Dam, the research took the environmental WD of the rivers into account as required by MoWR, GOI (2002) and MoEF, GOI (2006) (section 5.2.1.2). Figure 7.3 compares the projected annual WD given in the existing ILR plans with the one calculated in this study.

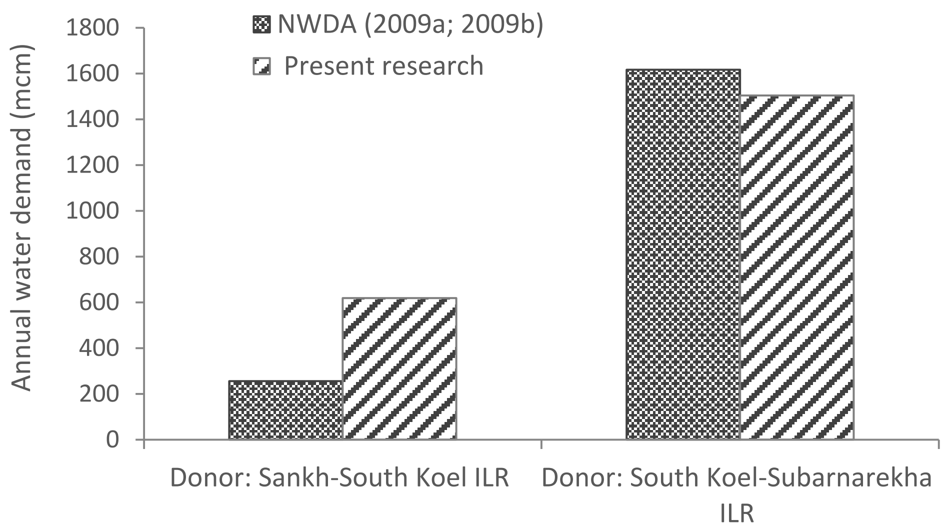


Figure 7.3: Projected annual water demand in 2050 in the upstream donor catchments of the two ILR links.

The present research found that WD in the contributing catchment area of the S-SK ILR link is more than double that reported in the ILR plan. On the other hand, the WD in the contributing catchment area of the SK-Sr link is slightly less than that reported in the ILR plan. WD projected in the present study is significantly higher in the upstream Tilga catchment (S-SK link) which is due to the high environmental WD in the catchment (Figure 7.3 and Table 7.1). However, WD projected by NWDA (2009b) is higher in the upstream and middle of Jaraikela (SK-Sr link), largely due to the higher irrigation and industrial WD. These are due to the inputs (data) in WD assessment which are discussed in detail in section 7.2.3.1.

Table 7.1: Different water demand (MCM) projected for 2050 in the donor catchments of the two ILR links.

	Different annual water demand (MCM)					
	Domestic	Livestock	Irrigation	Industry	Inflow to Rengali Dam	Environmental
Donor catchment of Sankh-South Koel ILR link						
NWDA (2009b)	10	0	94	12	139	0
Present research	17	4	86	0.4	0	511
Donor catchment of South Koel –Subarnarekha ILR link						
NWDA (2009b)	95	0	939	106	476	0
Present research	169	19	607	0.5	0	708

7.2.1.3 Annual surplus water at 75% dependability

NWDA (2009a, 2009b) projected annual surplus water available at 75% dependability in 2050 using WA, WD and return flows from the different WD; they proposed that parts of the surplus water be transferred to the Subarnarekha basin. The present research followed the approach taken by NWDA (2009a, 2009b) to calculate the surplus water. However, as WA and WD outcomes differed in the two studies, their surplus water also differed (Figure 7.4). It is observed that the projected surplus water by NWDA (2009a, 2009b) is remarkably high when compared with the estimates in the present study. The surplus is more than double in the case of the S-SK ILR project and triple in the case of the SK-Sr ILR project (Figure 7.4). These differences could be attributed to multiple WA and WD factors discussed in previous sections.

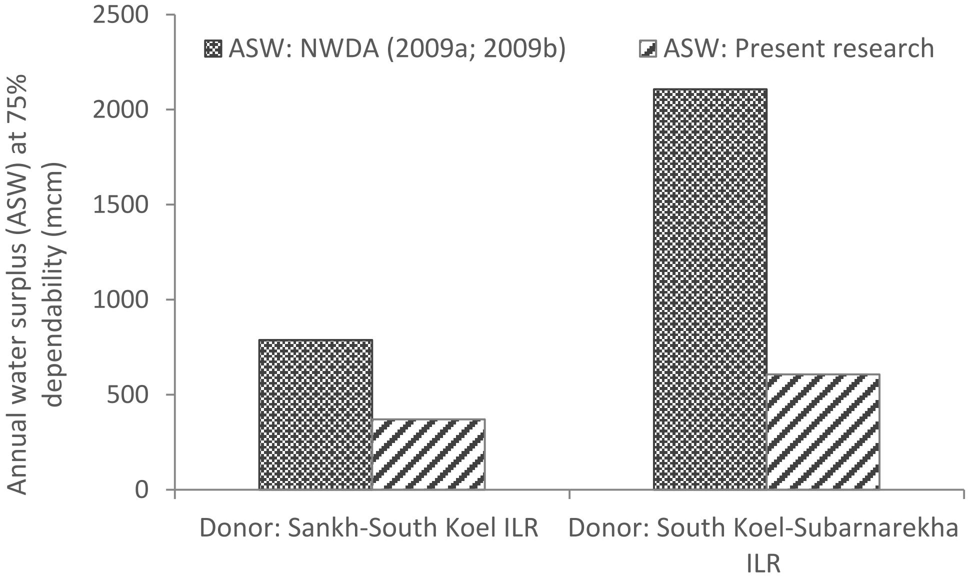


Figure 7.4: Annual surplus water with 75% dependability in 2050 at the upstream donor catchments of the two ILR links.

7.2.2 Functioning of the ILR links

The existing plans proposed that the S-SK ILR link will transfer 498 million cubic metres (MCM) of water from the catchment of the River Sankh (upstream Tilga) to the catchment of the South Koel River (NWDA 2009a). Out of the 498 MCM of water, 403 MCM will be further transferred to the Subarnarekha River basin via the SK-Sr ILR link, along with another 1389 MCM of water from the catchment of the South Koel River (upstream and middle Jaraikela catchment) to the Subarnarekha River basin (NWDA 2009b). The present research established that the two donor catchments will not have sufficient surplus water at 75% dependability on an annual scale to carry out these planned water transfers (Figure 7.5). The donor catchment of the SK-Sr link showed significant shortages of surplus water when compared to the amount of water transferred at the annual scale (Figure 7.5).

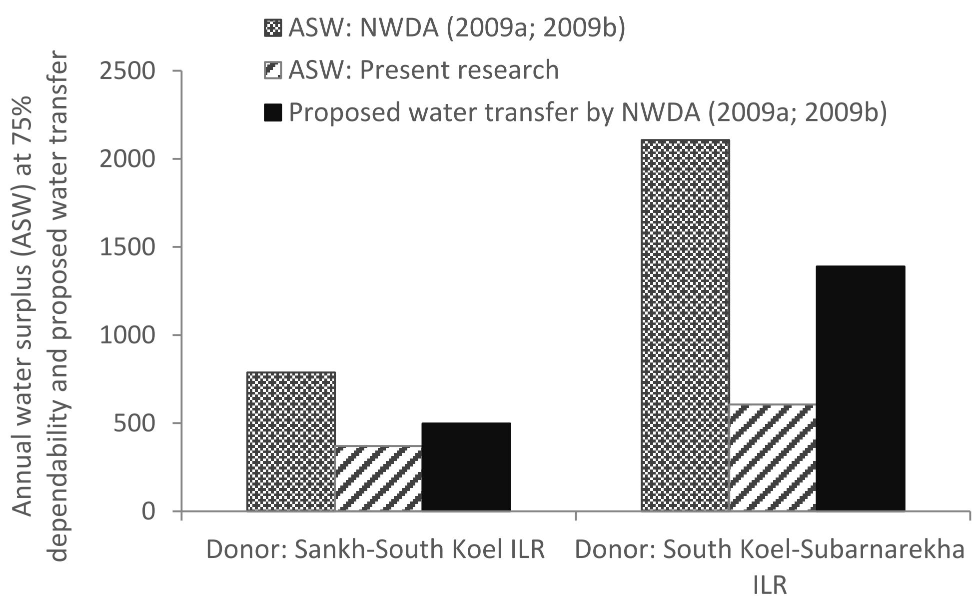


Figure 7.5: Annual surplus water with 75% dependability in 2050 at the upstream donor catchments of the two ILR links alongwith their proposed water transfer.

As outlined in sections 2.3.1.3 and 3.4.1, NWDA (2009a, 2009b) did not perform water-balance assessments at the seasonal or monthly levels. However, they claimed that both ILR links will function throughout the year to provide the proposed amounts of monthly water transfer in the reports although it remained unclear how they arrived at this suggestion (Figure 7.6).

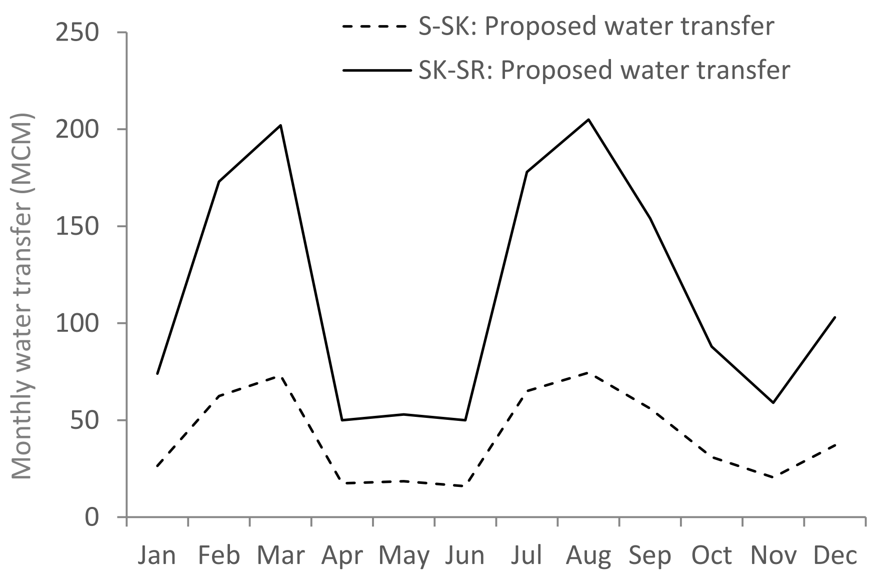


Figure 7.6: Proposed monthly water transfer of the two ILR links, Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) (NWDA 2009a, 2009b).

To examine the proposed water transfer at the seasonal scale, the planned monthly water transfer of both links was compared to the seasonal WA in their respective donor catchments (Figure 7.7). The comparison revealed that during non-monsoon months, both donor catchments will have insufficient water to transfer (Figure 7.7). In fact, the two donor catchments will be water deficient during non-monsoonal months, which have also been corroborated by the risk assessment carried out in Chapter 6 that highlighted a highly significant risk in meeting the WD of two donor catchments (Table 6.12 and Table 6.13). Water transfer from these catchments could aggravate their water-deficit situation as demonstrated by the simulation of links (Table 6.14-Table 6.17). The water deficit in these donor catchments will directly impact the water transfer through ILR links which is evident from the significantly high risk and vulnerability of ILR links observed during the water transfer simulation in non-monsoon months (Table 6.23-Table 6.31).

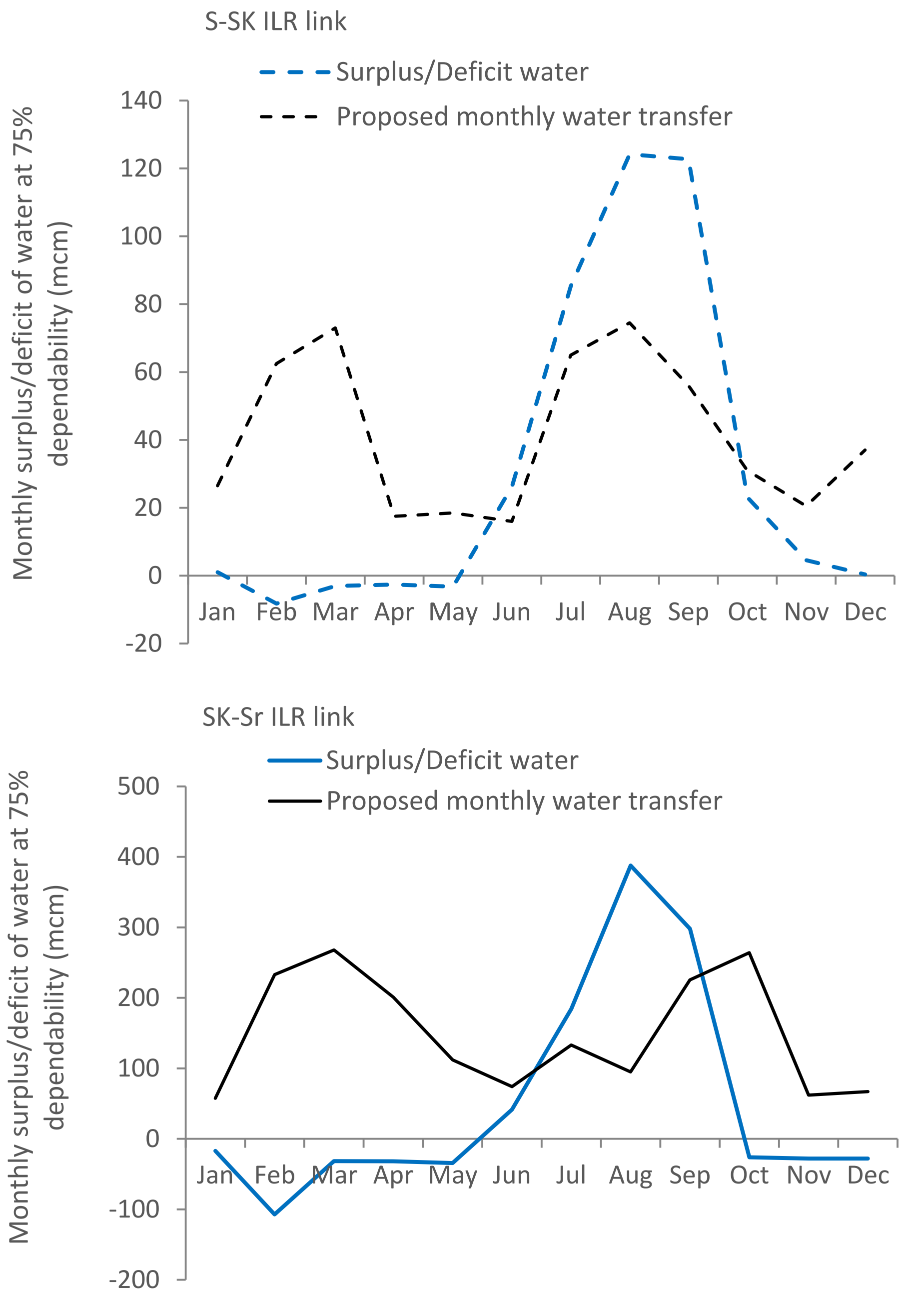


Figure 7.7: Proposed monthly water transfer of Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR links (NWDA 2009a, 2009b) along with the projected monthly surplus water with 75% dependability in 2050 at the upstream donor catchments of respective links.

To facilitate water transfers, storage structures such as reservoirs would be required to store water in the monsoon season as non-monsoon WA at 75% dependability is not sufficient to fulfil the WD in both of the donor catchments, let alone the water transfers from them (Figure 7.7). However, ILR plans only mentioned the construction of barrages (diversion dams) on the main rivers (River Sankh and River South Koel) at offtake points of the respective links (NWDA 2009a, 2009b). Here it should be noted that a barrage does not have a storage facility (Basu 2017) and is largely used as a river-flow regulator (Challa 2002). To regulate the river-flow for diversion, barrages are used to raise the water level of the river by a few metres during low-flow periods i.e. non-monsoon season while they allow the extra water to flow during high-flow periods i.e. monsoon season (Punmia 1992) due to no storage facility. Thereby, with no storage facility for monsoon water and critically low non-monsoon season WA (sections 4.4 and 5.3.2), the claims for water transfer by NWDA (2009a, 2009b) appear impossible to fulfil.

7.2.3 Data and approaches

The critique below discusses potential reasons for the overestimates of water availability in the NWDA studies. This section also outlines data and approaches used in the present research while responding to the issues observed in the two ILR plans.

7.2.3.1 Data

i) Water availability

As mentioned above and discussed in section 3.4.1, NWDA (2009a, 2009b) used annual flow data from 34 years (1964-65 to 1997-98) observed at Jenapur HOC (Figure 7.1), located 418 km and 360 km downstream from the outflow points of the S-SK and SK-Sr links respectively, to calculate the natural water yield at 75% dependability. This water yield included data for reservoirs along with future imports[3] of water in its catchment-area (covering 37,574 km^2). Subsequently, this annual water yield at Jenapur HOC was used to calculate annual WA in the donor catchments of the S-SK and SK-Sr links, despite the facts that the two donor catchments: first, were located considerably far away from Jenapur, second, only

[3] NWDA (2009a, 2009b) reported that there is no current import in Brahmani-Baitarani River basin; however there is a plan by the Government of Odisha (2004) to import 2985 MCM from neighbouring Mahanadi River basin to Tikra (downstream of Rengali Dam). NWDA (2009a, 2009b) also reported that there is no export from the basin.

covered approximately 5% and 19% of the catchment-area of Jenapur, and third, better datasets with finer spatial and temporal resolution were available (sections 5.2-5.3). It was also noted that the annual data over-estimated WA outcomes as they ignored seasonal variability. Therefore, the use of such large spatial as well as temporal scale data for comparatively small catchment-areas caused the following issues:

1. It generalised the hydrological variability within the basin (section 4.4).
2. It ignored the flow distribution caused by seasonal variability (sections 4.4 and 5.2.1.1) which is a critical factor influencing the WA in the donor catchments exhibiting significantly low WA in non-monsoon season (section 5.3).
3. Future import of water from Mahanadi was accounted for in the WA of the donor catchments (170 MCM in S-SK and 584 MCM in SK-Sr ILR projects). However, at present, the two donor catchments do not have any current or future plans for the importing of water (section 5.2).

Similar issues were noted in other ILR plans (Smakhtin et al. 2007, 2008). These issues can explain the overestimation of WA by ILR planners in the donor catchments, particularly in the case of the SK-Sr ILR project (Figure 7.2). Subsequently, it resulted in an overestimation of the potential monthly water transfer by the ILR planners.

Yet long-term daily discharge datasets (34 years) are available for nearby HOC (Tilga 40 km downstream of S-SK starting point and Jaraikela 38 km downstream from starting point of SK-Sr link) through the Water Resource Information System (WRIS) by GOI (India-WRIS webGIS 2016) depicting finer spatial as well as temporal resolution that could have been used by NWDA (2009a, 2009b) to achieve more accurate results of WA. The present research used these datasets to evaluate annual and seasonal WA in the catchments under study.

ii) Water demand

The existing ILR plans used the district-level total population for 2001, but they did not provide the source for the data. NWDA (2009a, 2009b) used the projected national level growth rate for 2050 by the United Nations (1995) and the national-level percentage of urban population for 2050 by the United Nations (1993) to project urban and rural populations for 2050 despite the availability of finer administrative (such as district) level population data from the Census of India by the Ministry of Home Affairs (MHA), GOI with records from as early as 1872 (MHA, GOI 2017). Additionally, urban and rural water use rates were different in the two ILR projects (NWDA 2009a, 2009b) despite the similarity in socio-economic characteristics of their catchments (section 4.5.1). As a result, domestic WD estimated by the ILR planners does not provide an accurate representation of the real life situation, which undermines their credibility (Figure 7.8). To address these issues, the present research used the latest and finer administrative-level population datasets from the Census of India by MHA, GOI along with most commonly used water-use rate by NWDA (2016) to estimate the domestic WD for 2050.

Further, ILR planners used different water-use rates for irrigation. The rate used for analysis of the SK-Sr link was significantly higher despite the similarities in the characteristics of both donor catchments (sections 4.3-4.4). Additionally, discrepancies were noted in the reporting of irrigation WD by NWDA (2009b) (section 3.4.1) due to which the irrigation WD was raised in the water-balance assessment for the SK-Sr ILR project. These consequential errors led to higher estimation of irrigation WD in the catchment (Figure 7.8). Also, the errors diluted the credibility of reports. Research presented in this thesis verified the irrigational projects mentioned in both ILR plans with the irrigation project data given by the Regional Remote Sensing Service Centre (RRSSC) of GOI (Sharma et al. 2007) and included all projects provided by NWDA (2009a, 2009b) (section 4.5.2). Due to the inconsistencies noticed in both ILR plans, estimates in this thesis largely used irrigation-areas provided by Sharma et al. (2007) which were verified by GIS mapping. The research used the average of irrigation water-use rate given in both reports due to three reasons: rice as the principal crop grown, similarities in the climate and soil of the study area (Punmia 1992) (sections 4.3-4.4) and unavailability of field-data for the irrigation water-use rate. These changes were reflected in irrigation WD through their noticeably reduced quantity (Figure 7.8).

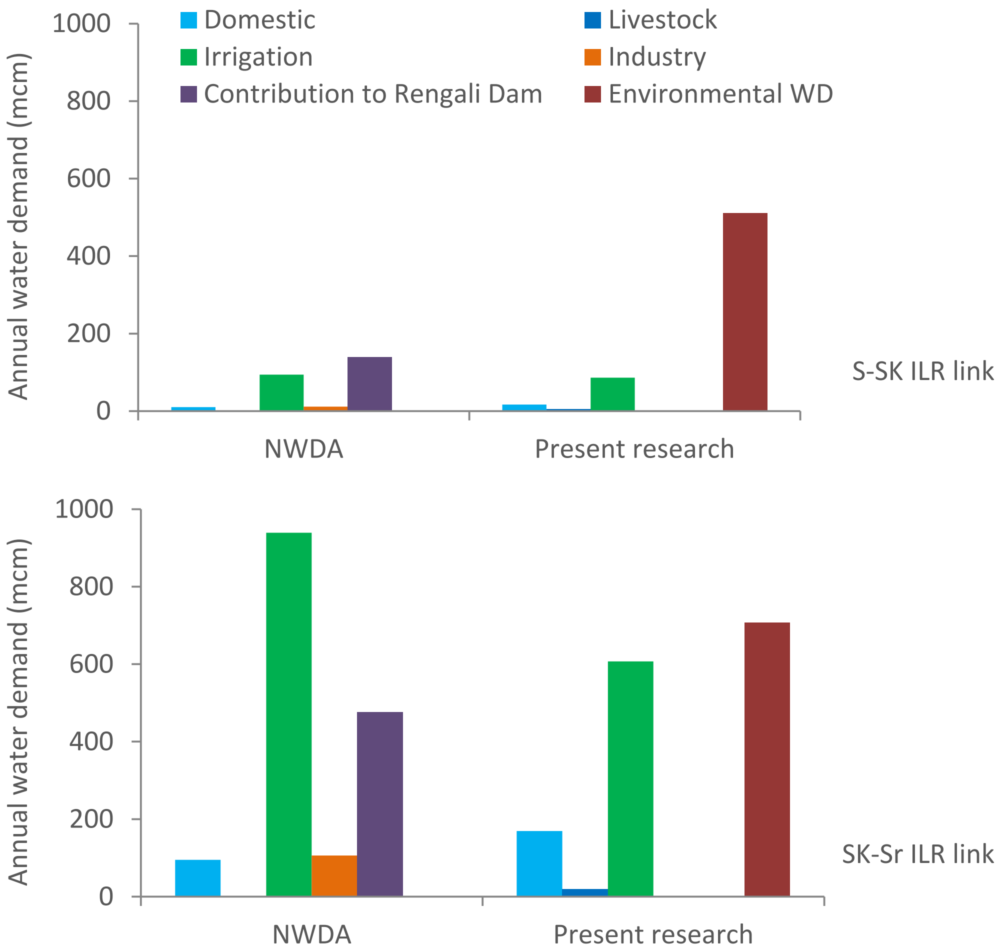


Figure 7.8: Comparison of projected annual water demand (MCM) in 2050 by NWDA (2009a, 2009b) and present research.

Further, NWDA (2009a, 2009b) took industrial WD to be equivalent to domestic WD by citing non-availability of data for industrial WD. However, at the present time, donor catchments have insignificant industrial activities (section 4.5.3). Thus industrial WD projected by NWDA (2009a, 2009b) is overestimated (Figure 7.8). The current research addressed the unavailability of industrial water-use data by using the product of the industrial area provided by MSME (2016) and the national average industrial water-use rate, and then verified it with the industrial WD reported by WR-GOJ (2012) (section 5.2.1.2).

Furthermore as mentioned above, NWDA (2009a, 2009b) considered downstream commitment to Rengali Dam but ignored Environmental WD as required by Indian laws (MoWR, GOI 2002; MoEF, GOI 2006) (section 3.4.1). Last but not least they made an unverified assumption for livestock WD and did not include it in their calculations of WD. The present research addressed these issues by including an environmental requirement and livestock WD in its assessments (Chapter 5-6).

In general, it can be stated that different WD were either under- or overestimated as previously indicated by Vaidyanathan (2003). The present research attempted to address the issue by cautious selection of WD parameters, related inputs from credible sources and by the verification of WD outputs.

Overall comparisons of inputs in ILR plans suggests that although NWDA (2009a, 2009b) attempted to represent the water balance as accurately as possible, they ignored scale and sources of inputs, missed important variables, showed irregularities in reporting and made unverified assumptions. As a result, both ILR plans overestimated the potential water surplus (Figure 7.4) which formed the basis of both proposed ILR projects with exaggerated water-transfer targets (Figure 7.5). Thus, these inconsistencies indicate flaws in the approaches followed by the ILR planners which are discussed below.

7.2.3.2 Approaches

i) Concept of surplus and deficit

Similar to the other ILR plans, to decide for the S-SK and SK-Sr ILR projects, NWDA (2009a, 2009b) used the 'concept of surplus and deficit catchment' based on an unpublished paper by Mohile (Bandyopadhyay & Perveen 2003, p.8). According to the concept, ILR planners analysed the catchment as one unit. They used the total WA (surface water) and total WD (domestic, irrigation, industry, and downstream commitment) within the catchment to determine whether it is in surplus or deficit (Figure 7.9). This methodology used by ILR planners was primarily criticised for neglecting the environmental requirement in the river basin, disregarding the ground water and excluding the livestock WD in the river basin (Alagh 2006).

Mohile (2006) acknowledged most of the criticisms and advised ILR planners to improve their ILR reports. However, NWDA (2009a, 2009b) showed no improvement in this direction and continued using the criticized concept.

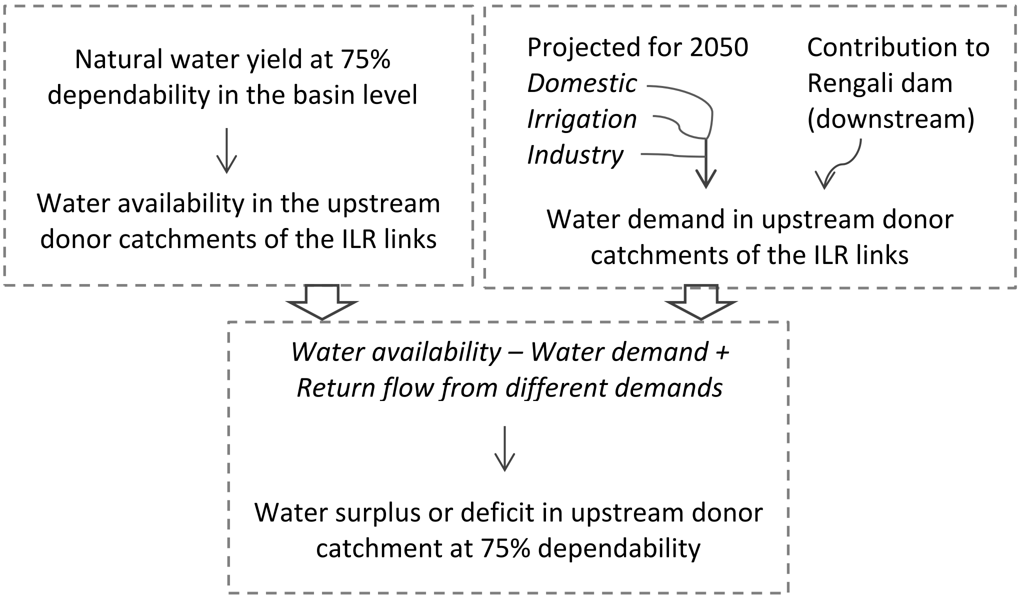


Figure 7.9: Water balance assessment process followed by (NWDA 2009a; 2009b)

The present research addressed these gaps and modified the methodology followed by the ILR planners (section 5.2) as presented in Figure 7.10. It changed some of the datasets used (section 7.2.3.1). The study further reviewed the prospects to include ground water, environmental requirements and livestock WD in the catchments. Groundwater constituted 4.9% of total WA in the region (CGWB 2014) thus was not to be included in the water-balance assessment (section 4.3.1.4). Further, according to MoWR, GOI (2002) and MoEF, GOI (2006), maintaining adequate environment flow in the rivers is an important requirement while planning any water resource project. Therefore, minimum environmental requirement flow was included in the assessments. Furthermore, as livestock farming is the primary rural activity in the region (Singh 2006), it was included in the assessments. The present research did not include separate WD for the downstream commitment to the Rengali Dam (Figure 7.10) as it included the environmental WD of the rivers which already ensured a significant portion of river-flow (45-71% of the WA at 75% dependability per annum in different catchments) to flow downstream.

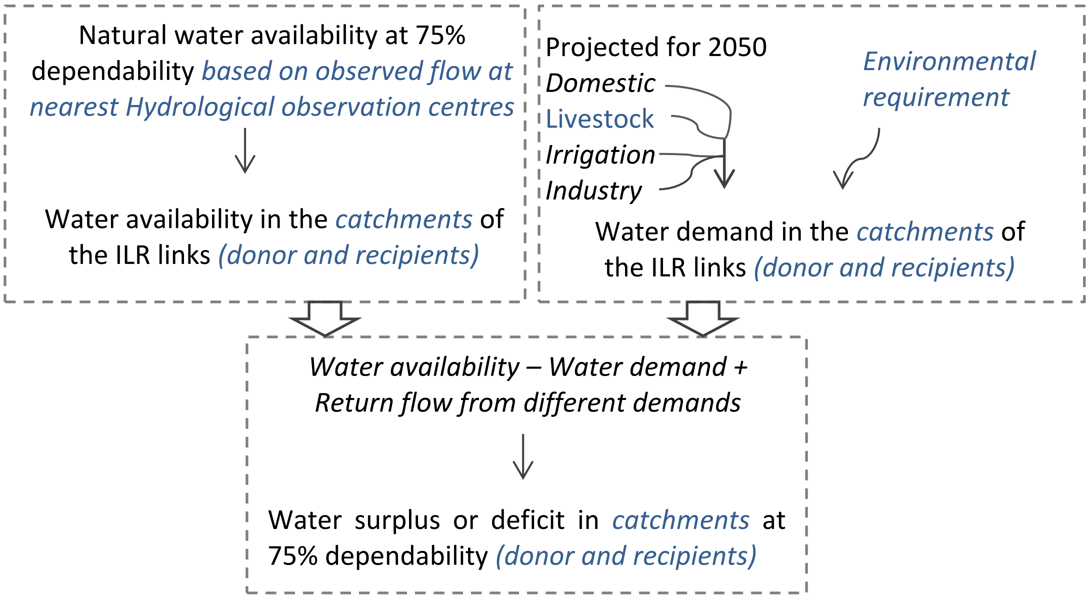


Figure 7.10: Modified version of water balance assessment process followed by NWDA (2009a; 2009b). Additions are highlighted in blue italics.

ii) Supply-orientated versus integrated approach

As mentioned above, NWDA (2009a, 2009b) ignored assessment of WA and WD in the recipient basin. Thus, they could not provide clear evidence in support of high WD in the recipient basin i.e. the Subarnarekha River basin. However, NWDA (2009a, 2009b) asserted high WD in Subarnarekha River basin as a reason to transfer the water to it, which indicates their supply-orientated approach preferring conventional hydraulic missions for water management, which in turn favours the recipient basin (Gupta & van der Zaag 2008). Such thinking is also evident in other ILR plans (D'Souza 2003). However, such an approach has been challenged extensively at the global scale (UNESCO 1999; Klein 2007) as instead of satisfying the growing need in the recipient basin, it could lead to further WD (Gohari et al. 2013). The growing concerns led to the development of IBWT criteria-sets (section 2.24) which indirectly endorse integrated management of IBWT involving the sustainability of both donor as well as recipient catchments (Gupta & van der Zaag 2008). National water policy (2002) by MoWR, GOI (2002) also advocates an integrated approach. The present research used this approach, which facilitated a cohesive platform based on established IBWT criteria-sets, to examine the performance of the S-SK and SK-Sr ILR links and their catchments. It assisted in combining the interests of donor and recipient catchments together; a prerequisite for their collective and sustainable development.

iii) Best-practice methods

NWDA (2009a, 2009b) considered only upstream donor catchments in its decision-making (Figure 7.1 and Figure 7.11).

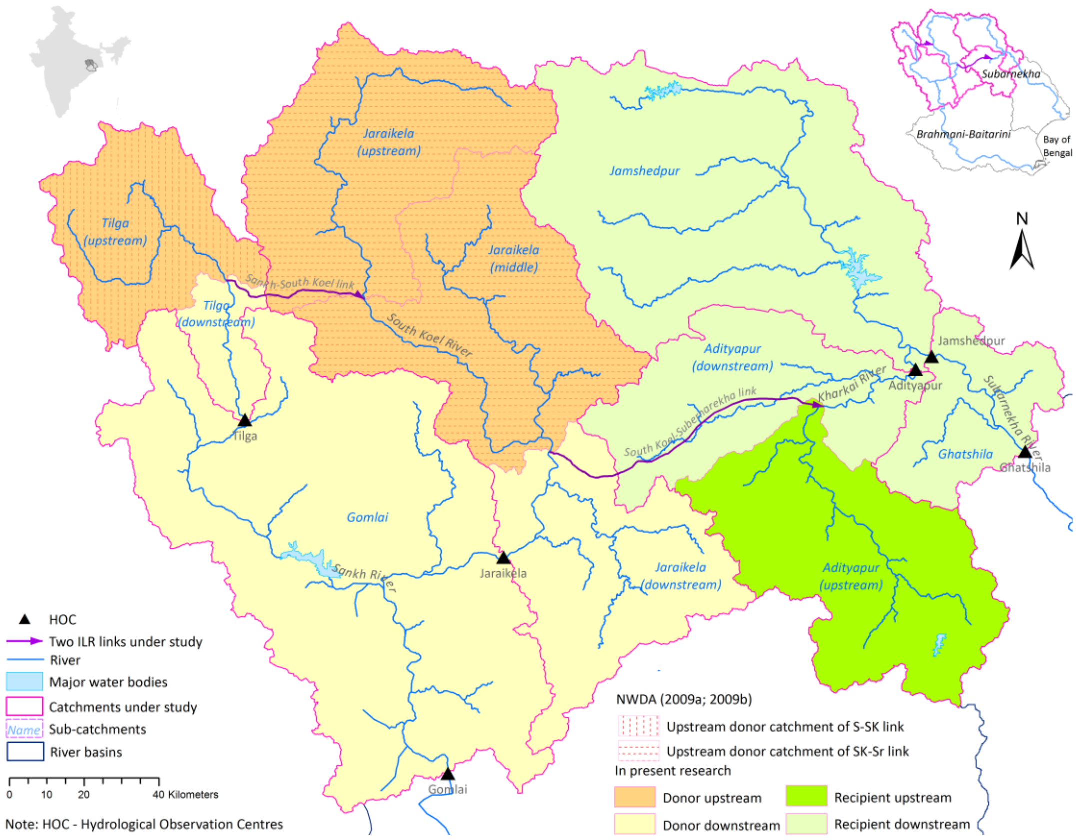


Figure 7.11: Catchments used by NWDA (2009a, 2009b) in comparison to the catchments used by present study in accordance with IBWT criteria-sets.

Like other ILR projects (section 2.3.1.3), NWDA (2009a, 2009b) decided to transfer water only on the basis of these upstream donor catchments being in surplus, and not on the basis of genuine WD in the recipient catchments. They neither examined downstream donor catchments, which could be affected by water abstraction, nor did they examine the recipient basin, which could be self-sufficient in meeting its demand or could have genuine WD. Thus, they overlooked the best-practice approaches in IBWT decision-making which advises water transfer to another basin only in the case when there is genuine current or future WD in the recipient basin based on reasonable growth, after exhausting all possible sources of water within the recipient catchment (section 2.2.4). As a result, they failed to fully justify the two ILR projects and could only provide vague benefits in the defence of both projects. The same attitude is seen in other ILR plans (Gupta & van der Zaag 2008). Adhering to published IBWT criteria-sets could have enabled the ILR planners to justify their decisions more fully. The present research addressed this gap and followed the accredited IBWT criteria-sets while evaluating the two ILR projects (Chapter 5-6) and included upstream as well as downstream catchments of both donor and recipient basins (Figure 7.11) in its assessments (section 3.2), thus the research worked towards the sustainability of all catchments involved.

Further, the existing ILR plans of these two IBWT projects are largely engineering-orientated and appear to ignore field characteristics such as hydrological and socio-economic patterns in their decision-making process (section 7.2.3.1). However, as discussed in sections 2.2-2.4, IBWT projects are wicked in nature, and thus need a hybrid approach in their planning and management. This hybrid approach is reflected in the research framework adopted in the present research (section 3.2); the primary purpose of this research was to gain a holistic and multi-disciplinary understanding of the catchments (Chapter 4). This multi-disciplinary understanding assisted in the identification, examination and explanation of elements and processes involved in the water-balance within the study area, leading to the development of an integrated assessment for the two ILR links (Chapter 5) and the exploration of risk and vulnerabilities involved in the two projects (Chapter 6).

iv) Generalisation in reporting

Both ILR plans by NWDA (2009a, 2009b) followed an organised structure which helped in the cross-referencing of the two reports, along with their referencing to other ILR plans. Both ILR plans presented technical details; however, only generalised descriptions were given which showed several discrepancies (discussed in sections 2.3.1.3 and 3.4.1. NWDA (2009a, 2009b) appeared to be inconsistent, for instance when they mentioned rainfall irregularity due to the monsoon in the proposed irrigated area but ignored the influence of monsoon while calculating the water balance in the donor catchments. Given the whole area has a monsoon climate, such inconsistencies by ILR planners generates distrust in their reporting. Further, ILR planners have been criticised for the lack of transparency in their reports leading to misinformation and then controversies (Prabhu 2008). The present research encouraged transparency by reporting on all issues involved in the decision-making process of the two ILR projects under study. The details are discussed in section 7.3 and their broader contexts are explained in section 7.4.

With this discussion of data and approaches used in the two ILR plans, the causes of overestimations of the surplus water are clear; and raise doubts about the justification given by the ILR planners, which are discussed in next section.

7.2.4 Policy evaluation

Both ILR plans by NWDA (2009a, 2009b) advocated for the water transfer by giving following reasons which are critically discussed below:

i) Surplus water in the donor catchments

As discussed above, the ILR planners of both links claimed surplus water in their donor catchments (section 7.2.1; Figure 7.4). However, the present research pointed out that although both of the catchments do have a surplus, they do not have enough water to transfer the proposed amounts (Figure 7.5). The present research further outlined that the surplus water in the donor catchments of both ILR links is only available during the monsoon season and both of the catchments face water deficit during non-monsoon seasons (Figure 7.7). Therefore, the donor catchments themselves are in need of water during periods of low flow. This seasonal influence on surplus WA was ignored by NWDA (2009a, 2009b). Both ILR plans showed over- or underestimation in either WA or WD or both (section 7.2.1). These subsequent errors weaken the credibility of existing ILR plans and thereby challenges the premises of surplus water taken by NWDA (2009a, 2009b) to validate the water transfers. These challenges are further strengthened by the outcomes of the present research which noted increasing risks in meeting WD at both of the donor catchments (Table 6.5-Tabel 6.6 and Table 6.12- Table 6.13).

ii) High industrial water demand in the Subarnarekha River basin

NWDA (2009a, 2009b) stated that transferred water will be used to meet the high industrial WD in Subarnarekha River basin. However, they did not provide evidence in support of their statement that there is high industrial WD in the Subarnarekha River basin, and if so whether the basin needs extra water from another basin to address that need currently or in the future. The present research noted high industrial WD in the Subarnarekha River basin (Table 5.5-Table 5-6) with 10 major industries (including 3 proposed) at the downstream of SK-Sr link (section 4.5.3). However, it also noticed that the Subarnarekha River basin showed no risk in meeting its current or future industrial WD (Table 6.5-Table 6.6 and Table 6.12-Table 6.13). In fact, the basin appeared self-sufficient to fulfil its own WD for the foreseeable future. Thus, the finding from the present study directly questions this foundation of meeting industrial WD in Subarnarekha River basin by NWDA (2009a, 2009b).

iii) New areas under Irrigation

With transfer of water through ILR links, NWDA (2009a, 2009b) claimed to add new areas of irrigation in their recipient basin (Figure 7.12). Both ILR links will bring newer cultivable areas under irrigation on its way to the recipient catchments and will cover 104 km^2 in the case of S-SK and 72 km^2 in the case of SK-Sr ILR project. The extra area of potential cultivation will be stand alone in the case of the S-SK link[4] while constricted in the case of the SK-Sr link (Figure 7.12).

[4] Here it should be noted that CA of the S-SK link which falls in its recipient catchment (upstream and middle Jaraikela) could not be verified for overlapping with CA covering 780 83 km^2 of separately planned future irrigation projects as exact location of latter was not available

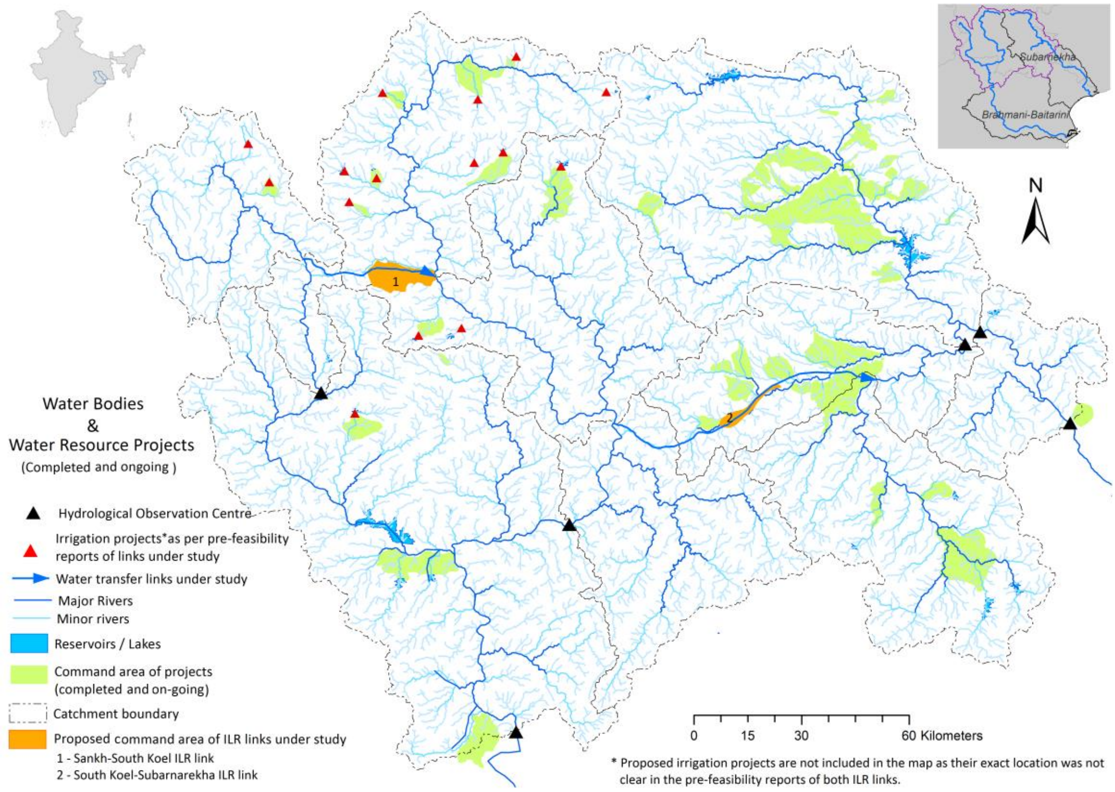


Figure 7.12: Command area of completed and on-going irrigation projects along with command area of both ILR links.

However, the recipient catchments of both links already have considerable area under existing, on-going and proposed irrigation projects (supported by their own water); 1205 km^2 in the recipient catchment of the S-SK link (425 km^2 in existing and on-going schemes and 780 km^2 in planned schemes) and 718 km^2 in the recipient catchment of the SK-Sr link (completed and on-going projects) (section 4.5.2). Therefore, when compared to existing irrigation projects and those planned within the recipient catchments, the small command area added by the proposed ILR plans will add very little value.

iv) Navigation

NWDA (2009a, 2009b) mentioned that water transfer to Subarnarekha basin will assist in making the River Subarnarekha navigable. However, Rao (1979) outlined that the River Subarnarekha is only navigable until a point 30 km from the sea coast (Bay of Bengal) due to various existing insurmountable characteristics such as restricted and unreliable river-flow. Government of Jharkhand is reportedly considering building a port near Ghatshila (Biswas 2003). Given the location of Ghatshila approximately 184 km upstream from the mouth of River Subarnarekha (Figure 7.1) and at 80 metres above mean sea level (MSL), the claim to make the River Subarnarekha navigable around Ghatshila or anywhere below it but within Jharkhand[5] seems highly ambitious and needs thorough investigation. Without this intensive investigation, transferring water for this questionable aim does not sound judicious.

Thereby, the reasons referred by NWDA (2009a, 2009b) to construct the two proposed ILR links hardly stands valid and raise serious concerns about the justification of the two projects.

7.2.5 Summary of the ILR critique

The critical assessment of the feasibility studies for S-SK (NWDA 2009a) and SK-Sr ILR links in 2009 (NWDA 2009b) has outlined that, due to several errors, the projected surpluses of water are exaggerated. The surplus water will be unavailable during dry periods within the year as their donor catchments are most likely to face water deficits during the non-monsoon season. The plans followed a traditional supply-focused approach and overlooked current best-practices available in IBWT decision-making and in the field of water resource management. The presence of several discrepancies undermined the credibility of the reports. The critiques of policies in the two ILR plans pose the question of whether the water transfers are worthwhile if they:

1. have unreliable WA within the year,
2. could aggravate water deficit in the donor catchments,
3. are unsure about their requirement in the recipient catchments, and
4. barely show any prospect of fulfilling the claimed benefits (irrigation and navigation).

Overall, the plans give an impression that they are favouring the recipient catchments at the expense of the donor catchments. As discussed above and in

[5] The lowest altitude in Subarnarekha River basin within Jharkhand is around 40 metres MSL.

previous chapters (Chapter 4-6), the recipient catchments certainly have high WD, especially in domestic and industrial areas; however, they showed no alarming risks in meeting their WD although some challenging situations were visible during dry periods. Thus they are relatively self-sufficient in meeting their WD both currently and for the foreseeable future. On the other hand, the donor catchments also display extensive WD which is noticeably higher in environmental WD and for future irrigation requirements. In addition to these WD, donor catchments, especially Jaraikela the major donor catchment of the S-SK-Sr project, face critical challenges in WA due to the prevalent intra- and inter-annual hydrological behaviour. Thus, they urgently need water management interventions to address their own water-deficits both currently and in the foreseeable future. Therefore, the ILR planners of the S-SK and SK-Sr ILR links must reconsider and revisit their decisions and plans for the two links.

7.3 Science-supported policy

NWDA (2009a, 2009b) draw parallels with the other ILR plans, and thus has similar merits and discrepancies (sections 2.3.1.3 and 7.2). It is noted that the planning of the ILR projects lacks science-supported policy and that provides evidence for the ILR projects being contentious and lacking mutual agreement among their stakeholders. It is imperative for such large-scale infrastructure proposals to be supported by evidence-based policy in order to ensure their success and sustainability, as highlighted by NRC-US (1992) and Loucks et al. (2005). It is also crucial that plans, methodologies and the data on which proposals are based are in the public domain (Solanes & Gonzalez-Villarreal 2009). Without this data democratisation, it is difficult to gather support from the wider public and engage communities impacted by such schemes (Lund 2012). This thesis demonstrates the essential role of evidence based policy and data democratisation in the IBWT decision-making process.

7.3.1 The role of science

The hybridity and wickedness of IBWT decision-making demands the careful planning of these projects, based on sound science covering different disciplines associated with it (Biswas 1977; Lund & Israel 1995; Prabhu 2008). Developed countries have responded to this call and since the 1970s a shift has been visible in the planning and management of their IBWT projects (Biswas 1977; NRC-US 1992). In contrast, developing countries are lagging behind (WCD 2000) as evident from their technical emphasis (Matondo 2002) under their supply-oriented approach (D'Souza 2003); it is also evident in the ILR planning (sections 2.3.1.3 and 7.2) as agreed by Smakhtin et al. (2008) and Verdhen (2016) and could be related to the pace of scientific development (Gupta & van der Zaag 2008). Thus, it is imperative for the Indian IBWT planners to be attentive and learn from global experiences and advice, ensuing that they apply these lessons in the planning of ILR projects (Chellaney 2011); however, little has been done by the ILR planners towards this goal (Pasi 2012; Verdhen 2016). The research undertaken in the present thesis, demonstrated the way in which robust science can support IBWT decision-making.

7.3.1.1 The established IBWT criteria-sets

The increasing trend in IBWT projects and their range of impacts prompted concerns from water managers which resulted in the development of criteria-sets for the evaluation of IBWT projects (Kibiiy & Ndambuki 2015). Although, several IBWT criteria-sets have been proposed (section 2.2.4), the one proposed by Cox (1999) has been applied in several IBWT projects and has been well-received by IBWT managers around the world (Bruk 2001; Pittock et al. 2009). Therefore, on the advice of Bruk (2001), the research undertaken in the present thesis followed the IBWT criteria delineated by Cox (1999) (section 5.2.1) that comparatively examined the donor and recipient catchments involved in the two ILR projects under study for their water surplus/deficit (Chapter 5) and associated risks and vulnerabilities (Chapter 6). This comparative investigation of donor and recipient catchments together ensured the sustainability of both catchments, in line with Kibiiy & Ndambuki (2015), and supported the integrated approach as suggested by Loucks et al. (2005), reducing the possibility of favouring one catchment over another as advised by Gupta & van der Zaag (2008). Thus, this evidence based comparison of donor and recipient catchments provided the arena for the bringing together of various stakeholders in order to facilitate a mutual discussion and/or agreement which is beneficial for the ILR project and all its stakeholders, as recommended by Iyer (2003b).

7.3.1.2 The understanding – holistic and multi-disciplinary

In order to deal with the hybridity and wickedness of IBWT projects (section 2.2.2.2), Gupta & van der Zaag (2008) suggested that a holistic and multi-disciplinary understanding of the catchments must precede the quest for any water-transfer possibilities; the same was also advised for the ILR projects by Bandyopadhyay (2012). This advice was followed in the present thesis and the outcomes have been discussed in sections 4.3-4.6 which includes: landscape characteristics (in light of Colby 2003; Biggs et al. 2007), hydrological behaviour (in light of Ceballos & Schnabel 1998; Bracken et al. 2008; Morán-Tejeda et al. 2012; Burt & Weerasinghe 2014) and socio-economic conditions (in light of Rosenzweig et al. 2004; Iglesias et al. 2007; GWP 2009). As expected, the understanding developed regarding the status and trends of these different bio-physical and socio-economic components in the present research stage assisted during the later stages of the research (Chapter 5-6). It was especially relevant in identification of vital inputs (e.g. including livestock WD in light of Singh 2006) and in making informed assumptions (e.g. non-inclusion of groundwater in light of CGWB 2014) as advised by Alagh et al. (2006) and Bharati et al. (2008). Further, the gained multi-disciplinary knowledge also provided explanations for further research findings, such as the higher risks noticed in the catchments contributing to the S-SK and SK-Sr links (sections 6.5-6.6) due to their hydrological and socio-economic patterns (section 4.4); thus, it could be used for the justification of research outcomes as projected by Bandyopadhyay (2012). In this way, the holistic and multi-disciplinary knowledge of the project area supported in deciding the strategies of the IBWT evaluation process, as anticipated by Gupta & van der Zaag (2008).

7.3.1.3 The integrated approach in IBWT decision-making

The IBWT decision-making process includes understanding water management in the donor and recipient basins (Gupta & van der Zaag 2008) which critically relies on the complex WA and WD assessments (Asiliev 1977), involving multiple objectives and stakeholders with conflicting desires and requirements (Zhang et al. 2012); it is a wicked problem (Lach et al. 2005) and requires an integrated and transparent approach (Marquette & Petterson 2009). The use of IBWT criteria-sets establishes the arena for an integrated approach in the present research (Chapter 4-6) as advised by Gupta & van der Zaag (2008), ensuring the sustainability of both donor and recipient catchments as suggested by Loucks et al. (2005) and Kibiiy & Ndambuki (2015). The results of this research, whether related to different disciplines (natural or social), components (WA or WD) or scales (spatial and temporal), were assessed together to make sound, evidence-based IBWT decisions. For example, when only domestic, agricultural and industrial WD was projected for 2050, recipient catchments showed high WD (section 5.4) as claimed by NWDA (2009a, 2009b), although NWDA (2009a, 2009b) did not provide any evidence. This claim was contradicted when environmental WD was integrated into the WD assessment, as a result of which, the donor catchments showed high WD. Another instance showing the benefit of an integrated approach was when WA and WD were combined and compared across donor and recipient catchments (section 5.5). All catchments showed surplus water at the annual level, however when examined at the seasonal level, the donor catchment showed water-deficit in the non-monsoon season while the recipient catchments showed no water-deficit at the annual or monthly scale (although the surplus water was very low in non-monsoon months). Nevertheless, results contradicted the conclusions accepted by NWDA (2009a, 2009b) that donor catchments are in surplus while water is needed in the recipient basin (section 3.4.1). The effectiveness of an integrated approach was also evident while simulating the ILR links and the catchments, and in their subsequent assessments of current and future performances (Chapter 6). The risks involved in the functioning of both catchments, as well as the ILR links, were examined simultaneously for their interrelationship which assisted in taking decisions to ensure the overall sustainability of ILR links and their catchments (section 6.5), in line with Gohari et al. (2013).

7.3.1.4 The technical advantage

The planning and management of IBWT projects requires efficient and advanced tools due to their interdisciplinary and complex nature (Jain et al. 2008). Computer modelling is an indispensable tool for such projects as highlighted by Loucks (2008) and Sechi & Sulis (2010) and was used in the present study to simulate the two ILR links and their catchments (Chapter 6). In contrast to the existing ILR plans (NWDA 2009a, 2009b), the complete range of WA and WD was assessed under several explorative management scenarios following suggestions from Jain et al. (2005), Bharati et al. (2008), Höllermann et al. (2010) and Haasnoot & Middelkoop (2012). The influence of climate change and the water source used was also examined; albeit on a basic level which could be explored further in future studies. The simulation outputs culminated in a risk evaluation of the ILR links and their catchments (Hasimoto 1982) and predicted vulnerabilities of the ILR links (Gohari et al. 2013) at the annual and monthly scale (Smakhtin et al. 2008; Jain et al. 2005; Gohari et al. 2013). These outputs from the use of technical advancements, along with the outputs related to the water surplus/deficit (Chapter 5), indicated the sustainability of the S-SK and SK-Sr ILR projects and their catchments (sections 6.5-6.6), as anticipated by Loucks & Beek (2005).

Thus, the use of sound science from different disciplines assisted in gaining deeper insights into the IBWT decision-making process; the present research could therefore efficiently make informed decisions and accumulate evidence for the justifications of decisions made. Further, to gather support from the wider public as advised by Lund (2012), the research worked towards data democratisation in the planning and management of the IBWT projects (Solanes & Gonzalez-Villarreal 2009) which is discussed in the next section.

7.3.2 Data democratisation

Under the first objective, to uphold The Dublin Principles (WMO 2017), this thesis worked towards data democratisation as suggested by Solanes & Gonzalez-Villarreal (2009). Thus, it facilitates transparency and represents the voice of people, albeit indirectly, which was made possible through the data management undertaken in this thesis as discussed below.

7.3.2.1 Transparency and voice of the people

IBWT projects, being wicked problems, need a transparent approach encouraging collective participation of all stakeholders during both planning and management (Lund 2012). Transparency in IBWT decision-making encourages dialogue (Feldman 2001) and strengthens the justification for these projects (de Andrade et al. 2011); thus it has been long promoted by scholars (Prabhu 2008) and falls under The Dublin Statement on water and sustainable development (Solanes & Gonzalez-Villarreal 2009; WMO 2017). Still, the IBWT decision-making process lacks in transparency, leading to restricted or no public-participation in the process , largely seen in developing countries as highlighted by Matondo (2002) and Islar & Boda (2014) (section 2.2.2.2). The case of the ILR projects is no different as discussed in sections 2.3.1.3 and 2.3.2.2 despite the clear guidance from the National Water Policy (2002) of India (MoWR 2012). Lack of transparency has caused credibility-loss, misinformation, conflicts and delays in the ILR projects as outlined by Pasi (2012). In contrast to the ILR planners, and in order to facilitate transparency, this thesis used publicly available data and tools (section 3.3). All datasets used were sourced from multiple government departments. Also, the software and modelling tools used are largely available in the public domain; if they are not, they can easily be accessed with little effort, or a good substitute is available publicly. The methods used in the present research are known for their scientific value and straightforwardness, and are well cited by other studies. Therefore, the data, methods and outcomes of the present research can be easily interrogated by any person or organisation interested, enabling a platform for mutual discussions, as demanded by Iyer (2003b). Further, by facilitating the independent evaluation of the research undertaken by any interested parties, this thesis allows the engagement, albeit indirectly, of communities impacted by such schemes; nevertheless, it represents the voice of people, agreeing with Lund (2012). In this way, the research works towards reducing possibilities for conflict by gathering support from the wider public (Bruch et al. 2005) which would eventually allow smooth planning and management of the IBWT projects as anticipated by de Andrade et al. (2011). These efforts were made possible through the data management undertaken in this thesis.

7.3.2.2 The management of data

IBWT projects are large and complex in nature; thus, the IBWT decision-making process involves data management challenges ranging from its collection to representation (Narain 2000). The ILR managers have shown reluctance in maintaining transparent data management (Alagh et al. 2006) and no other information is available in the public domain other than the feasibility or detailed reports of the ILR projects (Smakhtin et al. 2007; NWDA 2017), undermining The Dublin Principles (Madhav 2010) and leading to conflicts and delays as discussed in the previous section. The present thesis worked for transparent data management, in order to encourage data democratisation, in line with Solanes & Gonzalez-Villarreal (2009); thus, it used publicly available data for the evaluation of the IBWT decision-making process (section 3.2.1). It resulted in significant challenges for the data management undertaken in this thesis, especially given the enormous range of components, parameters, scales and outputs, as anticipated by Narain (2000).

The collection of datasets was a significant challenge for this study due to the large number of variables used in the assessment as well as their availability from different platforms (Loucks et al. 2005). The collection of data was carried out in light of: data democratisation, relevance to present research (fundamental decision-level), reliability, data integrity, longer-term periods, currency, availability and the limitations of this doctoral research. The datasets used are detailed in section 3.3 and the variables used in the water-balance assessments are explained in section 5.2. The section discussing variables in the water-balance assessments was informed by the knowledge gained in Chapter 4 as well as by ILR plans and peer-reviewed literature (Chapter 5), as advised by Bharati et al. (2008). To ensure reliability, the study used datasets provided by multiple government departments (section 3.3). Only a couple of datasets were taken from other credible sources: The Digital Elevation Model was taken from United States Geological Survey (USGS) (2007) which was also used by GOI in their Water Resource Information System (India-WRIS webGIS 2016); industrial water consumption rates were taken from the database of United Nations (FAO 2015). The data integrity was maintained by using data from consistent sources; for example, the majority of datasets were taken from central Indian government organisations or reports by the Central Government of India (GOI) as the catchments under study spanned four different states of India. Jharkhand covered the largest portion (around 74%) of the study area and therefore some of the datasets from the Government of Jharkhand were used to verify the processed datasets, e.g. industrial WD from WR-GOJ (2012). Further, data with the longest period and latest availability were selected.

The processing of data largely involved scale-related issues due to varying spatial (Gupta & van der Zaag 2008) and temporal (Smakhtin et al. 2007) scales. The datasets were available at the administrative level, while this study required datasets at the catchment level. As the datasets are rarely available at the catchment level, the data based on administrative level was used. The research used data from the lowest possible administrative level in order to represent the real life challenges as accurately as possible. The district level datasets were found suitable for the purpose due to several factors: the availability of datasets, vast spatial scale as well as the complexity involved in the IBWT projects, and the time-limit of this doctoral research. These district level datasets were processed using appropriate methods to prepare data at the catchment level. Further, for the temporal scale, although daily-level datasets were collected, the results were analysed and represented on a monthly level as discussed in sections 5.2-5.3. Here it should be noted that the scale and process would have introduced some data loss (e.g. rainfall data conversion Ensor & Robeson 2008). However, due consideration was taken while finalising the scales and the data processing methods leading to the selection of the most appropriate and scientifically sound options available (discussed in relevant contexts/sections; e.g. industrial WD in section 5.2), as advised by Loucks et al. (2005). Discrepancies in some of the datasets, and unavailability of some others, made the data management task challenging (section 3.3) for example, datasets related to irrigation and industries (details in sections 3.3 and 5.2). Wherever required, the processed datasets were verified using secondary data sources (such as, in the case of industrial WD, by WR-GOJ 2012) or by other means such as GIS mapping (for example, the irrigation area by Sharma et al. 2007). Thereby, every effort was taken to represent the data as accurately as possible; limitations were minimised at their lowest possible level and kept in perspective while interpreting the outcomes of the research.

The organisation of datasets was primarily based on their nature (spatial or temporal) and then on the basis of assessments carried out followed by the two major components, WA and WD, which is in line with Loucks et al. (2005). Efforts were made for the proper storage of data in order to ensure the confidentiality and protection from data-loss following Whyte & Tedds (2011). The effective representation of output data was challenging given the complexity of IBWT projects, the large number of analyses and outputs, and the two scales, annual and monthly level as highlighted by Loucks et al. (2005). Thus to counter the effect of wickedness of IBWT projects, the usage of effective and straight-forward graphs and charts was preferred, as suggested by Kirk (2016).

Thereby, with the support of science and by following data democratisation, this thesis efficiently tackled the hybridity and wickedness of the IBWT decision-making process.

7.4 The influence of hybridity & wickedness

The hybridity and wickedness of the IBWT decision-making process influenced the style of research adopted in this thesis (section 2.5) and caused complexities in the process. They are discussed below.

7.4.1 Style of research

As outlined by Gupta & van der Zaag (2008) and Kibiiy & Ndambuki (2015), the planning and management of IBWT has been very challenging, which has attracted scholars from a range of disciplines, to address its different aspects, grouped as six major concerns and discussed in section 2.2.2.2. These concerns have resonated in the ILR project (section 2.3.2), for which several recommendations were made in order to resolve them (sections 2.3.3 and 2.4). However, it appears from the ILR plans that major recommendations were either poorly addressed or ignored by ILR planners (Pasi 2012; Verdhen 2016) as discussed previously; and their traditional approach for the ILR decision-making continued (section 7.2.1-7.2.3). Also, the studies critiquing ILR projects were largely theoretical and provided few solutions to address the concerns raised regarding the project (section 2.3.2). Therefore, massive gaps were noted in the planning and management of the ILR projects (section 2.3.3). The present study explored these gaps (section 2.4); given the enormity (Ghassemi & White 2007) and complexity of IBWT projects (Swyngedouw 1999) as well as the duration of this doctoral research, it quickly became apparent that only a few gaps could be explored, and therefore, the fundamental gaps in the IBWT decision-making process were identified and addressed (section 2.5). To close the gaps, the study offered a methodological framework which culminated from several current and widely-acknowledged approaches ranging from integrated to data democratisation (sections 3.2 and 7.3.1), methods covering hydrological to socio-economic aspects (Chapters 4, 5 and 6) and recommendations made regarding planning and management of IBWT including ILR projects (sections 2.2.3.2 and 2.3.3).

In this way, this research addressed an applied problem and examined associated theories from different disciplines, following Loucks et al. (2005). It divided the complex problem of IBWT decision-making into a set of simpler problems, addressed individually but with a holistic and an integrated approach, as proposed by Lund (2012). Best-practice approaches and methods were applied to solve the IBWT problem in question (Chapters 4, 5 and 6). The thorough exploration of different relevant disciplines and methods provided better explanations for the processes involved in the IBWT decision-making, as anticipated by Bandyopadhyay (2012); the approach also strengthened the position to justify the decisions made as demanded by Pasi & Smardon (2012). The justification process was further supported by the data democratisation approach of this research which allowed this thesis to be cross-examined and thus enabled indirect public participation in the IBWT decision-making (Lach et al. 2005; Marquette & Petterson 2009). This way, the research facilitated a sound, scientific and transparent base to address the fundamental gaps in the IBWT decision-making process in India, as identified by Gupta & van der Zaag (2008). Ultimately, through this research agenda, the study encouraged sustainable development of the areas involved in IBWT projects, as highlighted by Kibiiy & Ndambuki (2015) which is in line with the sustainable development goals (SDGs) identified by UNDP (2017).

The research maintained an intention to neither support nor criticise the water transfers between basins. Instead, it worked on strengthening the process of IBWT decision-making in order to make informed IBWT decisions (section 2.5). With its neutral point of view, the research intended to support the ILR planners in making educated decisions in the ongoing planning for ILR projects. The intention to support ILR planners encouraged this research not to deviate drastically from the approach taken in ILR plans (section 3.2) so that, with no or minimal effort, the developed research framework can be used directly in the on-going ILR planning. The advantages of employing this research framework, as discussed in section 7.3, will enable the ILR planners to justify their decisions. As the data used in this case study are from government sources, the outcomes related to the two ILR links, S-SK and SK-Sr, can be promptly utilised for their planning and management.

7.4.2 Complexities encountered

In adopting the style of research discussed above, various complexities were encountered due to the large scale as well as hybrid and wicked nature of the IBWT decision-making process, such as finalising the scale of study, making assumptions, deciding the techniques to be used, and finalising the analysis level.

The S-SK and SK-Sr ILR links cover the upstream of Brahmani-Baitarani and Subarnarekha river basins; thereby any abstraction or addition of water would affect the downstream area in both basins. However, the basins cover large areas (section 3.4.2) implying constraints of scale, data and time-period for undertaking this doctoral research. Hence, determining the boundaries of the study area was complicated. This complexity was resolved by following Gurung & Bharati (2012) who observed that the immediate downstream catchments are most affected. The hydrological observation centres (HOC) with current and long-term flow data were identified for the rivers involved in the two ILR projects (India-WRIS 2016) and their catchment boundaries were used as the study area boundaries. In order to accommodate different requirements of several stakeholders involved in the IBWT projects, several assumptions are made in the IBWT decision-making process, which could influence the outcomes (Smakhtin et al. 2008). Therefore, the assumptions made in this study were well-informed and clearly outlined (Table 5.1; section 6.2.3.2). Furthermore, given the enormity and complexity of IBWT projects, it was difficult to finalise techniques to be used in the present research. Therefore, wherever required, the techniques available in similar studies/disciplines were examined and selected on the basis of their: relevance to this thesis, scientific value and straightforwardness (in light of Loucks et al. 2005; Lund 2012). For example, the selection of the water resource management model, for the simulation of ILR links and the catchments (section 6.2.3). Further, it was difficult to decide the appropriate depth/level of analysis required in each case, in order to achieve the purpose in question (e.g. influence of El Niño, the impact of climate change in meeting WD). In such situations, the depth of analysis was decided on the basis of its relevance to this thesis (sections 2.5-2.6); however, wherever further analysis-level would be beneficial for the IBWT decision-making, suggestions have been made to explore them in future studies. Other than the complexities discussed here, complications were also encountered in the data management which has been discussed in section 7.3.2.2. Similar to these complications, some other complex decisions were made whilst keeping the context of research in mind; they are discussed wherever they have been mentioned. For example, the decision related to annual and monthly WA (sections 5.4 and 5.6).

Thus, it is apparent that the research style adopted in this thesis was effective in handling the hybridity and wickedness of IBWT projects. Although complexities were encountered in this process, they were resolved according to the scope and limitations of this doctoral research. With the discussions above (section 7.3-7.4), it can be stated that the research undertaken in this thesis effectively used science-supported policy in the IBWT decision-making process and facilitated transparency in the process. Moreover, the research framework developed in this thesis is efficient in dealing with the complexities of the IBWT decision-making process. Based on the understanding acquired from the critique as well as from the discussions in section 7.3-7.4, this thesis draws recommendations for the IBWT projects in India and in general.

7.5 Recommendations

In light of the understanding developed through the research process and its findings, the thesis makes the following recommendations:

1. The IBWT decision-making process should be based on a holistic and integrated approach, including understanding of the donor and recipient catchment involvement in the IBWT project and the water availability and its demand in these catchments. The research findings support informed IBWT decision-making and promotes sustainable development of all catchments involved whether donor or recipient.
2. IBWT projects should follow established IBWT criteria–sets which primarily require IBWT planners to compare the water balances in donor and recipient catchments in order to ensure that the:
    2.1. The recipient basin is facing significant water deficit in current or future time after exploiting all its source of water availability.
    2.2. The donor basin has surplus water and does not suffer from current or future water deficit.
    2.3. The water transfer should not cause any current or future water deficit in the donor catchments.

This involves twofold assessments: first, water balance, and second, risk and vulnerability assessment. It strengthens the justification of water transfer projects by ensuring first, that surplus water in the donor basin can be transferred without harming its sustainability; and second, urgent and genuine water demand in the recipient basin, which cannot be met by the water resources available in it.

3. The planning of IBWT projects should include detailed characterisation of catchments involved in the IBWT projects as the understanding developed from it assists in the IBWT decision-making process by:
   3.1. Selecting all important variables to be used in the IBWT decision-making so that the decision-making process is based on a genuine representation of the water balance in the catchments involved.
   3.2. Identifying the underlying processes and patterns in the catchments which could influence water availability and its demand within the catchment. It assists in selection of methods to be used as well as in the explanations of outcomes of the IBWT assessments.
4. The IBWT projects should promote data democratisation as required by the Dublin statement on Water and Sustainable Development. It boosts the credibility of decisions made by enhancing transparency of the IBWT decision-process and allowing indirect public participation through facilitating cross-examination by anyone interested.
5. IBWT planners should ensure that data used in IBWT decision-making is the latest available, taken from reliable sources, represents the appropriate spatial and temporal scale considering the regional and seasonal variability respectively and maintains data integrity and coherency for all the areas involved so that it avoids any data discrepancies.
6. IBWT planners should ensure that the latest available and established techniques are used in the IBWT assessments as any limitation in the methods could restrict the exploration of IBWT potential which could then lead to ill-informed decisions.

In light of these recommendations, the study advises the following for the two ILR links, Sankh-South Koel and South Koel-Subarnarekha ILR projects and the catchments involved in these projects:

1. The two ILR projects will not be able to meet their potential aspirations and therefore their planners need to reconsider their decisions and revisit the existing planning of these links.
2. The catchments of Tilga and Jaraikela in upstream Brahmani basin (covering the donor catchments) need water management interventions to tackle the water deficit in them both now and in the foreseeable future.
3. The upstream part of the Subarnarekha basin (covering the recipient catchments) is capable of meeting both its current and future water demand. Therefore, the importation of water from another basin is not needed at this time. However, given the low WA in non-monsoon season, they need improvements in their water management.

7.6 Summary

The present chapter used the findings of the research undertaken in this thesis to critique the current ILR plans of Sankh-South Koel and South Koel-Subarnarekha ILR projects, outlined the specific contribution of this thesis and provided recommendations for IBWT projects in India and in general.

The critique of ILR plans outlined that the surpluses of water projected by the ILR planners in the two donor catchments are exaggerated and will be unavailable during the non-monsoon season. The ILR planners followed the traditional supply-oriented approach, overlooked best-practices in the IBWT field and lacked in evidence-based policy; thus the credibility of the ILR plans is undermined and justification given for the two projects is insufficient. Therefore, with the planning of these two ILR links in progress, the ILR planners appear to favour the recipient catchments at the expense of the donor catchments. The consequences of these plans could be grave for the donor catchments as they themselves are water-deficient at the current time and in the foreseeable future time period. Therefore, the ILR planners of the S-SK and SK-Sr ILR links must reconsider and revisit their decisions and plans for the two links.

The present thesis effectively demonstrated the use of robust science from different disciplines in the IBWT decision-making process, which assisted in making informed IBWT decisions efficiently and provided supporting evidence for these decisions. Further, the research ensured data democratisation in the IBWT decision-making process by using publicly available data. It set the arena to bring together various stakeholders of IBWT projects for mutual discussion and/or agreement, which is beneficial for the ILR project and all stakeholders involved. Thus with the use of science–supported policy and data democratisation, the thesis efficiently demonstrated a process for tackling the hybridity and wickedness of the IBWT decision-making. The research style adopted in this thesis effectively addressed complexities encountered in the IBWT decision-making process, in line with the scope and limitations of this doctoral research. Further, based on the understanding acquired the thesis drew recommendations for the IBWT projects in India and in general. The developed research framework can be used directly in the on-going ILR planning. It will enable the ILR planners to justify their decisions. As the data used is from widely-available government sources, which are relevant to the ILR links, the outcomes of this research for the two ILR links, S-SK and SK-Sr, can be promptly adopted.

Chapter 8 Conclusion

8.1 Introduction

Water availability (WA) is unevenly distributed around the world, as a result of which water managers encounter immense challenges in meeting water demand (WD) as they look for new water-supply sources. Inter-basin water transfer (IBWT) is a sought-after solution which has brought prosperity to many areas; however it has also prompted several concerns (Chapter 2). The traditional IBWT decision-making process is one of these concerns, especially in developing countries like India. The challenge of effective and integrated decision-making is addressed in the present thesis by exploring two IWBT projects under the Inter-linking of rivers (ILR) Projects in India, namely the Sankh-South Koel (S-SK) and South Koel-Subarnarekha (SK-Sr) ILR links. In this evaluation, the thesis used best-practices available (Chapter 2 and 3) to gain a holistic and integrated understanding of the catchments (Chapter 4), assessed the potential water surplus/deficit in the catchments (Chapter 5) and evaluated the risks encountered by the catchments and the proposed links. The vulnerabilities of ILR links were also assessed (Chapter 6). The outcomes were used to critique the existing ILR plans and draw recommendations for the IBWT projects in India and in general (Chapter 7).

This chapter revisits the aim and objectives of the research conducted (section 8.2), reflects on the strengths, weaknesses and constraints of the research undertaken in this thesis (section 8.3) and provides suggestions for future work (section 8.4).

8.2 Meeting the aim and objectives

This thesis aimed to evaluate the decision-making process of the S-SK and SK-Sr ILR links in India using publicly accessible data and tools. The thesis achieved its aim by accomplishing the following objectives:

Objective 1: Use of publicly available datasets and tools in order to evaluate their roles in understanding the IBWT decision-making process.

With the first objective, the research effectively explored the role of publicly available data and tools in IBWT decision-making, in order to encourage data democratisation within it. By following the first objective, the study intended: to make the research reliable and transparent but with minimum cost-implications, and to allow the research to be easily interrogated by any person or organisation interested, enabling a platform for mutual discussions. It was difficult to achieve this objective due to various reasons, such as: locating credible datasets, securing data at suitable spatial and temporal scales, discrepancies and incoherencies in the datasets from different sources (e.g. irrigation), unavailability of some datasets (e.g. industrial) (section 3.3) and the selection of the model to be used (section 6.2.3.1). These challenges were successfully addressed with assistance from and/or cross-verification by other peer-reviewed studies and government reports. In this way, the thesis successfully achieved its first objective which encouraged transparency, allowed indirect public participation in the IBWT decision-making process; thus it boosted the reliability of decisions made. It established publicly available datasets and tools exist and that these are suitable for evaluating proposals for IBWT.

Objective 2: Characterisation of the catchments involved in the two ILR projects under study (landscape, hydrological and socio-economic).

Through the second objective, this thesis provided a holistic and multi-disciplinary understanding of the catchments involved in the two ILR projects under study, covering current and relevant landscape features, hydrological behaviour and socio-economic patterns in the catchments, which could contribute to determining their water-balance patterns (Chapter 4). The most difficult challenge in attaining this objective was the identification of variables and methods from different disciplines to be used for the characterisation of the catchments. A large set of literature comprising government reports and peer-reviewed articles from different disciplines was consulted which assisted in identifying the variables and methods most relevant. The successful achievement of this objective depicted prevailing bio-physical, hydrological and socio-economic conditions in the catchments that assisted in: identification of vital inputs, informing assumptions and supporting the explanations of outputs in the assessments carried out in this thesis (Chapter 5 and 6). The knowledge gained through this objective also contributed in critiquing the two ILR plans (Chapter 7).

Objective 3: Development of an integrated assessment of water availability and demand in the donor and recipient catchments of IBWT projects enabling an evaluation of existing IBWT plans for the links.

The research undertaken developed an integrated appraisal based on the established IBWT criteria-sets (Cox 1999), in order to examine the potential surplus/deficit of water in the donor and recipient catchments of the two ILR links (Chapter 5). The findings from this objective estimated WA in the catchments at 75% dependability, projected WD for 2050 and assisted in critiquing existing ILR plans (section 7.2). The integrated appraisal developed under this objective was used as the basis for the simulation of the two ILR links and the catchments in subsequent research stage (Chapter 6). The significant challenge in the attainment of this objective was to maintain the understated intention of constructive criticism as well as the intent to strengthen the IBWT decision-making process in India (sections 2.5 and 7.4.1). This challenge was overcome by modifying the conceptual framework of the ILR planners using the best practice available in the IBWT planning and management and simultaneously refraining from any substantial deviation from the core conceptual structure of these plans (sections 5.2 and 7.2). Some of the challenges faced while working on this objective include: decisions related to inclusion of groundwater and/or livestock, water-consumption rates and monthly variations in WD. These inputs could influence the outcomes related to WA and demand, exaggerating the water surplus or deficit in the catchments. Challenges were resolved by taking data and time constraints into account in evaluating the IBWT decision-making process. The outcomes related to these inputs were scrutinised and verified using published government information and reports. Another important issue while working on this objective was to decide the minimum flow requirement of the rivers which was resolved by referring to related government reports and instructions. Thereby, the objective was fulfilled effectively and provided the water balance of the catchments enabling the critiquing of ILR plans. It also ensured that the developed research framework can be readily used by the ILR planners with no or little effort.

Objective 4: Performance assessment of the ILR links and their catchments through their simulation under a range of scenarios using the methodology developed.

Under the fourth objective, the ILR links and their catchments were simulated under a range of current and projected scenarios for 2050 on the WEAP platform (Chapter 6), using the integrated appraisal developed under the third objective (Chapter 5). The performances of the links and catchments were assessed through risks and vulnerabilities to explore: first, the influence of water transfer on the catchments and second, functioning of the two ILR links. Some of the issues faced during simulation were already resolved while achieving the third objective, such as decisions about inclusion of groundwater and/or livestock. Two significant challenges in accomplishing this objective were the development of scenarios and the representation of results. For the development of scenarios, several explorative scenarios were considered from which suitable scenarios were sorted using an iterative process on the basis of their relevance towards the aim of this thesis. Further, representation of outputs in a meaningful way was challenging due to a total of 826 output entities at the annual scale and 11,184 output units at the monthly scale. The problem was resolved after several trials of different ways of representing the data. Thereby, this objective was successfully achieved and outlined that the two main donor catchments suffer considerable and heightened risks in meeting their own

WD at the current time and in the foreseeable future so the two ILR projects will be unable to meet their potential aspirations; also indicated by heightened risk and vulnerabilities of the two links themselves. Additional outputs of this objective include the indication of marginal influence by climate change as well as the type of water source fulfilling rural and livestock WD.

Objective 5: Recommendations for the IBWT decision-making process in India and in general.

The outcomes from objectives 1-4 of this thesis were used to draw the recommendation for both ILR of the links as well as IBWT more widely (section 7.5). Results suggest that the publicly available data and tools, a holistic and integrated approach and established IBWT criteria-sets should be used for the evaluation of IBWT schemes. Such an approach encourages detailed assessments of the characteristics, water balance and performances of the catchments as well as the functioning of water transfer links.

Following the realisation of all objectives, this thesis evaluated the decision-making process of the two ILR links by using established IBWT criteria and practising data democratisation under the Dublin principles. Subsequently, it made significant recommendations for the future decision-making process of the IBWT project, which enables a platform for a scientifically sound IBWT decision-making process, encourages transparency and allows indirect public involvement; thus, the research enhances the credibility of the decisions made empowering the justification of the IBWT projects.

8.3 Evaluation of research

This research used a transparent, interdisciplinary and integrated approach based on widely acknowledged IBWT criteria-sets which covered both donor and recipient catchments in the IBWT decision-making process. The study developed a research framework to assess high level decision-making surrounding IBWT projects whose three main components are: characterisation of catchments under IBWT projects, integrated assessment of water balance in those catchments and performance assessment of the two IBWT links and the catchments through their risks and vulnerabilities. The research framework developed covers detailed temporal and spatial scales, ensuing reliable outputs covering annual and seasonal levels. The research design upholds the coverage of local (e.g. livestock WD) as well as environmental needs in the rivers. It stimulates detailed assessments of characteristics, water balance and risks in the donor and recipient catchments as well as measuring the risks and vulnerabilities of the water transfer links. Moreover, its modelling environment provides flexibility of the scenario based assessments in the IBWT decision process, which in turn allows several likely scenarios to be considered (such as influence of climate change and type of water source for rural populations and livestock). Thereby, the research framework of IBWT decision-making developed in this thesis enhances the credibility of the decision made.

The reliability of this framework can be further improved if every single variable of the water balance in the catchment is included in the assessments. The assessment in this thesis included the essential variables which were highly significant to the water balance of the study area. The variables with least significance (e.g. ground water in the study area) were not included directly due to the data restrictions. They can be included in the recommended assessments in the developed research framework, as long as the data issues are solved. Including such data will improve the accuracy of decision outcomes. Further, the spatial scale of datasets used in the present thesis is either available at the catchment scale (WA) or are computed from the district scale (WD) dataset. Given the data availability as well as the doctoral research time-period and the high-level IBWT decision-making in this research, these spatial scales are reasonable because the research is able to identify the regional variability in its outcomes. However, use of the datasets with further refined spatial scale will enhance the spatial variation of the outcomes. Similarly, the water-consumption rates and monthly variations of WD used in this thesis are appropriate given the data, time and decision-level constraints; the accuracy of related outcomes could be further refined by using higher resolution datasets.

Marginal influences due to the impact of climate change as well as type of water source fulfilling rural and livestock WD were visible. However, these were not explored in detail due to the limitations related to data, time and the decision level. Furthermore, due to the complexities involved in the environmental assessments, the thesis used only basic methods to acknowledge the environmental requirements of the rivers and catchments, which was taken from government reports and instructions. Thus the assessment of environmental WD effectively outlined the role of environmental need in the water balance of catchments to ensure suitable standards of water quality and adequate biodiversity. However, such an approach cannot alleviate the subsequent need for a full evaluation of the environmental assessment of the IBWT project. Moreover, the study initially planned to include the perspective of Indian IBWT planners which would have brought interesting understanding to the research. However, it was quickly realised that interviewing ILR planners could inflate the scope of this thesis. Also, such discussions needed a framework in advance which could only be achieved by detailed investigations of current and proposed IBWT decision-making agenda that required time. Thus, it was clear that interviewing Indian IBWT planners would not be possible within the time frame of this doctoral research. Thus, the plan was dropped.

Nevertheless, the research carried out in present thesis is a best-estimate for the fundamental decision-making of the IBWT projects and further refining is less likely to be important at this decision-making stage.

8.4 Suggestions for future work

The evaluation of this thesis leads to a roadmap for possible future research which could include:

1. The research framework developed in this thesis could be further improved by the inclusion of all variables (such as groundwater) and use of refined datasets (such as water-use rates and irrigation datasets) and scales for a more accurate assessment of WA and WD.

2. The influence of EL-Nino could be explored in detail if long-term rainfall and/or flow data are available.
3. The influences of climate change as well as water source type used to meet rural and livestock WD could be investigated thoroughly in future studies.
4. Downstream commitment of rivers was not included in present research as it was noted that inclusion of downstream commitment would not produce any different results for the links under study. However, it would be good to include this commitment in future studies.
5. The vulnerability of catchments for failure in meeting WD could be explored in future works.
6. A detailed and more wide-ranging evaluation of the needs of the environment could be undertaken.
7. Socio-economic aspects were only studied spatially. Future studies could add value through detailed assessment of changes over time.
8. The viewpoint of ILR planners on the research framework developed in this thesis could be explored which might bring new insights to the IBWT decision-making process.

Apart from the suggestions evolved from the research undertaken in this thesis, there are gaps pertaining to the other five groups of IBWT concerns (section 2.4) which can be addressed in future studies, such as a detailed social impact study and an extensive economic evaluation of IBWT projects.

8.5 Summary

This thesis aimed to evaluate the decision-making process of the S-SK and SK-Sr ILR links in India using publicly accessible data and tools. In order to fulfil its aims, the thesis delineated five objectives which were effectively met. The research yielded a holistic and multi-disciplinary understanding of the catchments involved in the two ILR projects and bio-physical, hydrological and socio-economic trends were noted. The understanding developed assisted in identifying essential inputs for the assessments carried out in subsequent research stages. It also informed the assumptions made and supported the explanations of the later research outputs.

Subsequently an integrated appraisal of the WA and WD in the donor and recipient catchments of both ILR links was developed on the basis of the best-practices available in the IBWT field which provided potential annual and monthly surplus/deficit water at 75% dependability. Based on the integrated appraisal developed, both water-transfer links and their catchments were simulated for their performance assessments. The outcomes of this thesis include:

1. The water surplus projected in both links by the existing ILR planners is exaggerated at both the annual and seasonal levels.
2. The S-SK and SK-Sr ILR projects will fail to meet their projected aspirations.
3. The two donor catchments of Tilga and Jaraikela need water management interventions in order to deal with their water deficit in the current and the foreseeable future time-periods.
4. The recipient catchments are capable of meeting their WD in both current and future time-periods. Therefore, they showed no urgent need for the water-import from another basin. However, low WA in non-monsoon season was noted which needs water management initiatives.

Therefore the research suggested that the ILR planners need to reassess their decisions and revisit the existing planning of S-SK and SK-Sr ILR links. Finally, the thesis drew recommendations for the IBWT projects.

The integrated research frame-work developed in this thesis is based on science-supported policy and is capable of dealing with hybridity and wickedness of the IBWT projects. It encourages data democratisation in the IBWT decision-making process; it thus allows indirect public participation by facilitating the data, methods and outcomes to be interrogated by anyone interested. As a result, it enhances the credibility of the decisions made. Moreover, the developed research frame-work facilitates a platform to bring together various stakeholders of IBWT projects for mutual discussion and/or agreement, which is in favour of the project and its stakeholders.

The thesis followed a neutral viewpoint and focused on strengthening IBWT decision-making in India. The developed research framework can be used directly by the ILR planners with no or minimal effort. Additionally, the planners of S-SK and SK-Sr ILR links can promptly adopt the research outcomes as the data used is from widely-available government sources, which are relevant to both links. The thesis represented a best-estimate for the fundamental decision-making of the IBWT projects. Nevertheless, if data and time permits, the accuracy of the research outputs can be refined further according to the need of IBWT project.

Appendix A.1 Chapter 1

Major inter-basin water transfer projects in world along with their important facts.

Country (& province)	Project Name (with Donor & Recipient)	Year (Start / complete)	Capacity (km^3/ year)	Highlights (eg. source, benefits, concerns etc.)
North America				
Canada (British Columbia)	Kemano Project (Nechako(Fraser) to Kemano)	1950 / 1952	3.22	– Sewell (1984); Das (2006); Harrison (1996) – Industrial use (aluminium industry), Hydro-electricity – EIA carried out in 1987 which highlighted several environmental impact – Ecological disturbance, Sedimentation
Canada (Manitoba)	Churchill diversion scheme (Churchill River basin to Nelson River basin)	1972 / 1976	24.44	– Sewell (1984); Das (2006); Harrison (1996); Shiklomanov & Rodda (2004) – Industrial use (aluminium industry), Hydro-electricity
Canada (Quebec)	James bay Programme (La Grande) (Eastmain-Opinac, Fregate and Caniapisca River basins to La Grande River Basin)	1975 / 1983	52.9	– Shiklomanov & Rodda (2004); Das (2006); Sewell (1984) – Hydro-electricity – Significant change in flow, Ecological disturbance, Relocation of people (aboriginal)
USA (New York State)	Croton River Project (Croton river basin to New York City)	N.A. / 1842	0.16	– Howe & Easter (1971) – First IBWT of USA – Municipal use – Capacity derived using Howe & Easter (1971), Baggett (2009) and Mcnally & Tognetti (2002)

USA (New York State)	Catskill Mountains Project (Catskill mountains to New York City)	N.A. / 1915	1.06	– Baggett (2009) – converted unit of capacity from gallons to km^3 – Municipal use – Transferred water pollution
USA (California State)	Los Angeles Aqueduct (Owens valley to Los Angeles City)	1908 / 1913	0.59	– UNESCO (1999); Ghassemi & White (2007) – Municipal use, Ecological disturbance
USA (California State)	Hetch Hetchy Project (Tuolumne river to San Francisco city)	1913 / 1934	0.44	– Ghassemi & White (2007) – Municipal use – Ecological disturbance, Adverse environmental impact
USA (California State)	Mokelumne Aqueducts (Lower Mokelumne River Basin in Sierra Mountains to San Francisco City (east))	1925 / 1963	0.84	– Ghassemi & White (2007) – Municipal use – Water supply is vulnerable to drought, earthquake and flooding; hence, demand management is adopted in recipient basin
USA (California State)	Central Valley Project (CVP) (Sacramento river to San Joaquin Valley)	1937 / 1979	13.48	– Golubev & Biswas (1977); Ghassemi & White (2007); Micklin (1984), Brekke et al. (2008) – Irrigation, Municipal use, Industrial use, Hydro-electricity, Environmental use in recipient basin – Significant change in flow of donor river, Adverse environmental impact (number of migratory salmon reduced), Potential impact of climate change
USA (California State)	State Water Project (SWP) (Sacramento river to San Joaquin Valley and to Central & Southern California)	1957 / 1972	3.80	– Hirji (1998); Micklin (1984); Brekke et al. (2008) – Supplemented CVP – Municipal use, Irrigation, Industrial use, Hydro-electricity, Recreation, Flood-control, Environmental use in recipient basin – Adverse environmental impact, Potential impact of climate change

USA (Colorado State)	Colorado River Aqueduct (Colorado River to Los Angeles and San Diego in California state)	1933 / 1941	1.50	– Ghassemi & White (2007) – Municipal use – Inundation of valued land, Increased river erosion, Ecological disturbance, Least public participation, Adverse environmental impact
USA (Colorado State)	Colorado-Big Thompson Project (Big Thompson river basin to South Platte River basin)	1937 / 1959	1.22	– Northern Water (2016); Gichuki & Mccornick (2008); Ghassemi & White (2007) – One of the most successful and well managed IBWT – Irrigation, Hydro-electricity, Municipal use, supplement flow to South Platte River – Was designed to provide 0.382 km^3/ year but could not achieve its goal. – Public protest for adverse impact to wild-life reserve area and benefit distribution (was resolved successfully)
USA (Colorado State)	Fryingpan –Arkansas Project (Fryingpan River basin and Hunter Creek to Arkansas River basin	1964 / 1978	0.92	– Ghassemi & White (2007) – Municipal use, Irrigation, Industrial use, Hydro-electricity, Recreation
USA (New Mexico State)	San Juan – Chama Project (San Juan River basin of Colorado State to Rio Chama, a tributary of Rio Grande River basin)	1967 / 1976	0.51	– Ghassemi & White (2007) – Municipal use, Irrigation, Industrial use, Hydro-electricity, Recreation
Mexico	Cutzamala System (Cutzamala River of Balsas River basin to Mexico City)	1970s / 1990s	0.47	– Tortajada & Castelán (2003); Haddad (1991) – Municipal use – Water demand exceeded supply in basin

South America				
Brazil	Paraíba do Sul River Basin Waterway (Pariba do Sul River basin to São Paulo State in Upper Tietê River basin, Rio de Janeiro in Guandu River basin, and Minas Gerais State)	1913 / 1952	5.05	– de Andrade et al. (2011); Kumler & Lemos (2008); Columbia Engineering (2015) – Municipal use, Hydro-electricity – Adverse environmental impacts, Transferred water pollution, degradation of water quality, difficulties of maintaining adequate water flows in dry years
Brazil	Sistema Cantareira project (Piracicaba River basin to the Alto Tietê River basin)	1966 / 1973	1.04	– Rodrigues (2014); de Andrade et al. (2011) – Municipal use – Provides 60% of water supply to Sao Paulo – Adverse environmental impacts, Transferred water pollution, degradation of water quality, difficulties of maintaining adequate water flows in dry years
Chile	Teno - Chimbarongo Canal (Teno River of Mataquito River basin to Estero Chimbarongo sub-catchment of Rapel River basin)	1970 / 1975	2.05	– Gomez (2001)
Europe				
United Kingdom	Elan Valley Water Transfer Scheme (River Elan, tributary of River Wye in Severn River basin district to Birmingham City in Humber River basin district)	1893 / 1904	0.13	– Elan Valley Trust (2016); BBC (2014) – Water supply to Birmingham City – One of the oldest project – Water needs to be treated for its acidic nature
United Kingdom	The Kielder Water Transfer scheme	1973 / 1981	0.2	– McCulloch (2006); Gibbins et al. (2000) – Industrial use, Flow supplement to Tyne River – Ecological disturbance

Germany	Danube - Rhine IBWT project (Danube River basin to the Rhine/Main River basin)	1970 / 2000	0.15	– Schumann (1999) – Water scarce region with high water demand – Water demand exceeded supply in basin – Municipal use, Industrial use – Change of land use, change in flow, Ecological disturbance – Good example of public participation and awareness since early stage of planning – Not much opposition
Germany	Harz mountains water diversion (Harz mountains water to west and east area)	1928 / 1969	0.18	– Schumann (1999) – Municipal use, Irrigation, Flood protection, Recreation, – Ecological disturbance
Germany	Lake Constance water transfer system (Lake Constance water to Stuttgart, Tubingen or Heilbronn and many rural areas)	1954 / 1971	0.125	– Bodensee-Wasserversorgung (2015); Schumann (1999) – Municipal use, improve freshwater quality in low-flow period, helped to improve water quality of Lake – Public discussion
Finland	Paijanne water supply tunnel (Lake Paijanne to Helsinki City)	1973 / 1982	0.70	– Lemmelà et al. (1999); Sillfors (2001) – Water supply, Restoration of polluted rivers, hydro-electricity
Spain	Tagus – Segura Water Transfer (Tagus River basin (upstream) to Segura River basin)	1940 / 1978	0.6	– Gichuki & Mccornick (2005); World Wild Fund (WWF) (2007); UNESCO (1999) – Irrigation, Municipal use, Recreation – Stream flow reduction, Adverse Environmental impact (endangered species), Social conflicts, Increase in water consumption – Increasing water availability from an IBT can become a driver for unsustainable water use in the receiving area
France	Durance-Verdon water system (Durance River basin to Verdon River basin)	N.A. / 1849	3.15	– Comeau et al. (2014) – Was expanded several times since then – Irrigation, Municipal use, Industrial use – Distribution conflict

Croatia	Hydroelectric power plant (HEPP), Gojak (Zagorska Mreznica River to Dobra River then to HEPP, Gojak)	N.A. / 1959	1.58	– Bonacci & Andrić (2010) – Hydro-power – Donor and recipient river basin are affecting karst region.
Africa				
South Africa	Tugela-Vaal Scheme (Drakensberg Mountains in KwaZulu-Natal to the Vaal River catchment for use in the Gauteng and Free State Provinces)	1974 / 1982	0.35	– Slabbert (2007); Snaddon et al. (1998) – Augmentation of flow to Vaal River; Hydro-electricity – Inundation of valued land, Ecological disturbance (in later EIA)
South Africa	The Grootdraai Dam Emergency Augmentation Scheme (Kameel Riverand Elands River to Vaal River)	1994 / 1999	0.015	– Snaddon et al. (1998); Slabbert (2007); – Augmentation of flow to Vaal River
South Africa	Mooi-Mgeni Transfer Scheme (Mooi River basin to Mgeni River basin)	2000 / 2003	0.025	– Roberts (1999); van Niekerk & du Plessis (2013) – Water supply fully developed in recipient basin – Water demand management implemented and needed augmentation of water – Water supply to Durban Pietermaritzburg region
Lesotho / South Africa	Lesotho Highlands Water Project (Vaal River basin to Orange/Senqu River basin)	1986 / 2002 (up to Phase 1B)	0.82	– World Wild Fund (WWF) (2007); Muller (1999) – Industrial use, Hydro-electricity – Phase 1A and 1B completed. Phase 2 and 3 are due. – Electricity, royalties and infrastructure for Lesotho – Reduced flow rates and less–frequent floods of the Lesotho river basins, Adverse environmental impact (critically endangered Maloti minnow threatened), Relocation of Population, Inundation of valued land

Asia				
China	Jiang Shui Bei Diao (Yangtze River to Lake Weishan in Huaihe River Basin)	1961 / 1980	3.3	– Liu et al. (2013) – Industrial use, Irrigation
China (Gansu)	Yin Da Ru Qin (Datong River to Qinwangchuan, Yongdeng)	1976 / 1995	4.43	– Liu et al. (2013) – Municipal use, Industrial use
China	Yin Luan Ru Jin (Luanhe River to Tianjin City)	1982 / 1983	1.0	– Liu et al. (2013) – Municipal use, Industrial use
China	Yin Huang Ji Qing (Yellow River to Qingdao City, Huaihe River basin)	1986 / 1989	6.78	– Liu et al. (2013) – Municipal use
China (north-east)	Bei Shui Nan Diao (Songhua River to Liaohe River)	1994 / 2005	7.00	– Liu et al. (2013) – Industrial use
China	Wanjiazhai Water Transfer Project (WWTP) (Yellow river to Taiyuan city in Fen River basin)	1997 / 2007	0.64	– van Niekerk & du Plessis (2013); Qingtao et al. (1999) –
China (Xinjiang, East China)	Irtysh–Karamay–Ürümqi Canal (Project 635) (Burqin River to Ürümqi)	1996 / 2010	2.419	– IRBDCA (2010) – Water supply, Hydro-electricity
China	South North Water Transfer Project – eastern route (Downstream Yangtze River to Tianjin City, Jiangsu and Shandong provinces)	2002 / 2013	14.8	– Kozacek (2015); Liu et al. (2013); Ghassemi & White (2007); Zhang (2009) – Municipal use, Industrial use – Ecological disturbance, Salt-water intrusion, Relocation of people

China	South North Water Transfer Project – middle route (Danjiangkou Dam to Beijing, Tianjin, Hebei, and Henan)	2003 / 2014	13.0	– Kozacek (2015); Liu et al. (2013); Ghassemi & White (2007); Zhang (2009); Chen & Xie (2010) – Municipal use – Ecological disturbance, Salt-water intrusion, Relocation of people, Potential impact of climate change
China	South North Water Transfer Project – western route (Upstream Yangtze River to upstream Yellow River)	Under planning phase	20.0	– Liu et al. (2013); SNWDP-CSC (2016); Ghassemi & White (2007); Zhang (2009) – Municipal use, Industrial use, Irrigation in six provinces of Yellow River basin – Ecological disturbance, Salt-water intrusion, Relocation of people
Iran	Kuhrang Project (Phase 1 & 2) (Karoon River Basin to Zayanderud River basin)	1954 / 1985	0.46	– Abrishamchi & Tajrishy (2005); (Gohari et al. 2013) – Irrigation, Municipal use, Industrial use, Hydro-electricity – Ecological disturbance – Water demand increased in recipient basin after added water supply
Iran	Yazd Project	N.A. / 1999	0.1	– Abrishamchi & Tajrishy (2005); (Gohari et al. 2013) – Irrigation, Municipal use (yazd City), Industrial use, Hydro-electricity – Ecological disturbance – Water demand increased in recipient basin after added water supply
India	Kurnool Cuddapah canal (Tungbhadra River, a tributary of Krishna River to Pennar River basin)	1858/ 1882	2.68	– Francis et al. (2002); UNESCO (1999); NWDA (2016) – Irrigation – Alignment faulty
India	Periyar –Vaigai Project (Periyar River basin to Vaigai River basin)	1887/ 1896	1.29	– Vedanayagam (1965); NWDA (2016) – Irrigation, Municipal use, Hydro-electricity

India	Idukki Dam Project (Reservoir on River Periyar which supply water to Muvattupuzha Valley)	1969/ 1976	2	– Govt. of Kerela (2016) – Hydro-electricity, Irrigation in Muvattupuzha Valley
India	Ravi-Beas-Sutlej- Link (Indira Gandhi Canal) (Ravi and Beas river to Sutlej River)	1948/ 1963	9.36	– NWDA (2016); Singh (1997) – Irrigation, Municipal use – Only project with successfully achieving the irrigation goals (in Haryana and Rajasthan)
India	Inter-Linking of Rivers project	Under planning phase	174	– Jolly (2016); NWDA (2016); Pasi & Smardon (2012); Ghassemi & White (2007); NWDA (2015); (Jolly & Probe International 2016) – Irrigation, Municipal use, Flood-control, Drought mitigation, Industrial use – envisages to link 37 rivers of 20 major basins in India – called as "only way forward" by proponents – Criticised on several grounds
Australia				
Australia	Goldfield Pipeline Scheme (Helena River basin to Goldfield)	1898 / 1903	0.3	– DoE GOA (2016); Ghassemi & White (2007) – Industrial use, Municipal Use, Irrigation – High demand in recipient basin motivated this scheme – Water was pumped at eight station – Declared national heritage by Government of Australia (GOA) – Recognised as an international historic civil engineering landmark

Australia	Snowy Mountain hydro-electric scheme (Snowy River basin to Murray and Murrambridge River basins)	1951 / 1973	8.47	– UNESCO (1999); Ghassemi & White (2007) – Diverted 99% of flow upstream of Snowy River at Jindabyne dam (Ghassemi & White 2007) – Irrigation, Municipal use, Hydro-electricity – Ecological disturbance, Adverse environment impact, poor management practices, Relocation of people (aboriginal), reducing wetland, poor cost-benefit assessment, Inundation of valued land, sedimentation, No consideration to demand management
Australia	Morgon - Whyalla Pipelines (Murray River basin to Whyalla, Port Pirie, Port Augusta)	1940 / 1944	0.01	– Ghassemi & White (2007) – Water scare region with high water demand – Water demand exceeded supply in basin
Australia (Queensland)	Mareeba – Dimbulah Irrigation Scheme (Barron River basin to Walsh River Basin)	1953 / 1958	0.407	– Ghassemi & White (2007) – Irrigation
Australia	Thomson diversion scheme (Thomson Catchment to Yarra River basin)	1971 / 1984	1.07	– Viggers et al. (2013); Ghassemi & White (2007) – Municipal use – Ecological disturbance
Australia	Shoalhaven Diversion Scheme (Shoalhaven River basin to Wollondilly and Nepean River basins)	1971 / 1977	0.28	– Ghassemi & White (2007) – Municipal use (Supply to Sydney) – Adverse environment impact, High erosion, Ecological disturbance – Rapid sedimentation of dams, Change in morphology of donor river, Ecological disturbance, Adverse environment impact

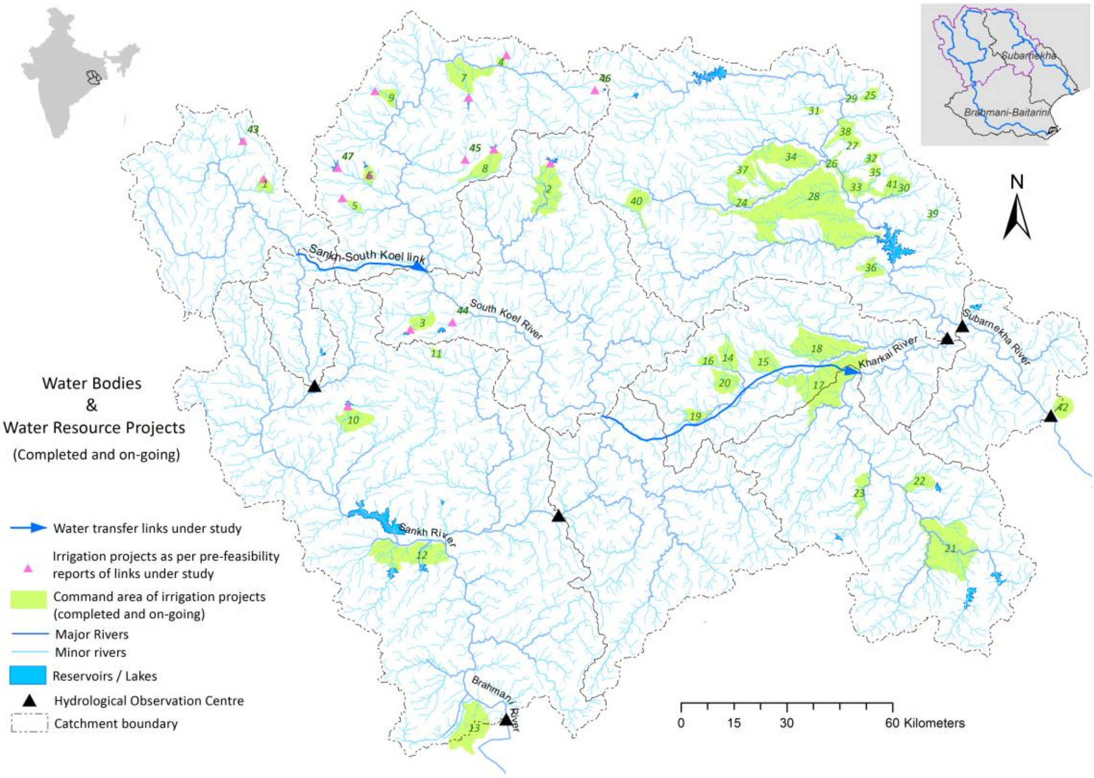
Appendix B Chapter 4

Appendix B.1 The net ground water availability in 2012 as per WR-GOJ (2012) covering three-fourth of the total study area.

WR-GOJ (2012) also reported the amount of ground water planned to be used and actually utilised which has not been reported by CGWB (2014).

Catchments by WR-GOJ (2012)	Coverage (%) of catchment area in present research	Net ground water (mcm)	Percentage of Net ground water	
			Planned to use	Utilised
Sankh	60% of Tilga; 44% of Gomlai	319	66	12.4
South Koel	96% of Jaraikela	694	85	37.9
Kharkai (excluding Subarnarekha)	69% of Adityapur	242	36	12.1
Subarnarekha (excluding Kharkai)	87% of Jamshedpur and 89% of Ghatshila	558	68	17.5
Total	74% of total area under study	1813	70	23.5

Appendix B.2 Irrigation projects (Completed, On-going and Proposed) in the study area



Sl. No.	Irrigation project	Area(km^2)	Total area (km^2)
Completed or On-going (Source: Sharma et al. 2007)			
Tilga			16
1	Jaipur Reservoir Scheme*	16	
Jaraikela			280
2	Latratu Weir Scheme**	90	
3	Tapkara Irrigation Scheme**	27	
4	Bucha Opa Reservoir Scheme**	6	
5	Khatwa Weir Scheme**	8	
6	Masaria Irrigation Scheme**	15	
7	Nandini Reservoir Scheme**	69	
8	Paras Weir Scheme**	45	
9	Phuljhar Weir Scheme**	19	
Gomlai			281
10	Chinda Reservoir Scheme*	49	
11	Larwa Irrigation Scheme	6	
12	Pitamahal	127	
13	Rukura	98	
Adityapur			718
14	Brahmani Irrigation Scheme	36	
15	Jensai Irrigation Scheme	43	

16	Nakti Reservoir Scheme	17	
17	Roro Irrigation Scheme	193	
18	Sona Irrigation Scheme	113	
19	Sonua Irrigation Scheme	19	
20	Vijay Irrigation Scheme	40	
21	Bankabahal kharkai	193	
22	Nesa	31	
23	Torlo Irrigation Scheme	34	
Jamshedpur			837
24	Aradih Irrigation Scheme	23	
25	Dimu	13	
26	Extension of Dangra	13	
27	Fakidi	13	
28	Kanchi Weir Scheme	404	
29	Karior	4	
30	Kestobazar	15	
31	Kita Weir Scheme	6	
32	Koerabera-I	11	
33	Koerabera-II	54	
34	Kokro Weir Irrigation Scheme	116	
35	Kulebera	9	
36	Palna Weir Scheme	27	
37	Riasa Irrigation Scheme	43	
38	Rupai	27	
39	Sankha	5	
40	Tajna Reservoir Scheme	37	
41	Turga	17	
Ghatshila			29
42	Murahir Reservoir Scheme	29	
On-going (Source: NWDA 2009a, 2009b)			
Tilga			71
43	Upper Sankh Reservoir Scheme	71	
Jaraikela			144
44	Dhansing Tola/Dansinghtoli Reservoir Scheme	25	
45	Kans Reservoir Scheme	34	
46	Basuki Reservoir Scheme	50	
47	Katri Reservoir Scheme	36	
Proposed Scheme (Source: NWDA 2009a, 2009b)			
Tilga			83
48	Laphri Nala (Suali Resrvoir Scheme)	29	
49	Lawa Reservoir Scheme	28	
50	Kundra /Kudari Nala (Korkotoli Reservoir Scheme)	10	
51	Samla Nala/Simla Nala (Tonga Reservoir Scheme)	16	
Jaraikela			780
52	Karanjtoli Reservoir Scheme	113	

53	Matukdih Reservoir Scheme	91
54	Koel Karo Reservoir Scheme	172
55	Basla Hydal Project	0
56	Tati Reservoir Scheme	25
57	Kisko Reservoir Scheme	8
58	Chamru Reservoir Scheme	29
59	Mahuatoli Reservoir Scheme	51
60	Porro Reservoir Scheme	19
61	Gorkho Reservoir Scheme	35
62	Chengari Irrigation Scheme	13
63	Dahnartoli Irrigation Scheme	36
64	Kanti Reservoir Scheme	35
65	Kunjla Reservoir Scheme	29
66	Pokta Reservoir Scheme	56
67	Banki Reservoir Scheme	25
68	Chipra Reservoir Scheme	11
69	Gagya Reservoir Scheme	14
70	Gamhar Reservoir Scheme	19

* mentioned in ILR plan of Sankh-South Koel ILR link by NWDA (2009a).
** mentioned in ILR plan of South Koel – Subarnarekha ILR link by NWDA (2009b).

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